AD 686178

AFFDL-TR-68-149

CRITICAL EVALUATION OF TRANSITION FROM LAMINAR TO TURBULENT SHEAR LAYERS WITH EMPHASIS ON HYPERSONICALLY TRAVELING BODIES

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TECHNICAL REPORT AFFDL-TR-68-149

MARCH 1969

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FOREWORD

This report was prepared by Mark V. Morkovin of the Research Institute for Advanced Study of the Martin Marietta Corporation at 1450 South Rolling Road, Baltimore, Maryland 21227. This work was performed under Air Force Contract No. F33615-67-C-1662; "Critical Review of Boundary Layer Transition" between April 10, 1967 and August 30, 1968.

This contract was initiated under project number 1366, "Aerodynamics and Flight Mechanics," task number 136606, "Boundary Layer Transition," and was funded by Laboratory Director's Funds. The work was administered under the direction of the Air Force Flight Dynamics Laboratory, Research and Technology Division. Successively, Mr. R. Jensen and Mr. E. D. McElderry were project engineers for the Laboratory.

Manuscript was released by the author August 1968 for publication as an AFFDL technical report.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

This review report represents an attempt to evaluate critically the available data on high-speed boundary layer transition to turbulence and to interpret the apparent agreements and contradictions within some rational framework. Special attention was paid to the more documentable discrepancies between reported results as touchstones of conceptual models and instability theories. Experiments with "microscopic" information are used as backbone of conceptual models, both linear and nonlinear. Linear instability results are used as a point of departure for the examination of current controversial questions of transition reversal with cooling, unit Reynolds number effect, effect of aerodynamic noise in supersonic wind tunnels, etc. Hopefully, more discussion and clarification will be generated by the present, at times blunt comments. Throughout, efforts at such clarification led to suggestions for possible fruitful research, theoretical, experimental, and applied. Many of the ideas put forward really represent a consensus of the many specialists at different laboratories the author had consulted. One of the objectives was to help to create such a consensus as to the best avenues of approach to hypersonic transition.

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LIST OF SYMBOLS

A/A_i	Ratio of disturbance amplitudes
$C = C_r + iC_i$	Wave speed
k	Roughness height
L/D	Lift to drag ratio
L	Length
M	Mach number
$\dot{m}$	Mass transfer rate
Re, Re_δ, $Re_{\delta*}$ R_θ	Reynolds number; based on boundary layer thickness, displacement thickness and momentum thickness
Re_k	Reynolds number based on roughness $ku(k)/\nu$
Re/L	Reynolds number per unit length
S	Entropy
T	Temperature
U, V	Free stream velocity
u', v', w'	Velocity fluctuations in the x, y, z directions respectively
x_k	Position of roughness behind leading edge

GREEK LETTERS

$\alpha = \alpha_r + i\alpha_i$	Wave number
β	Falkner-Skan variable
δ	Boundary layer thickness
δ^*	Displacement thickness
θ	Momentum thickness
ωx, ωy, ωz	Vorticity components
ν	Kinematic viscocity

SUBSCRIPTS

e	Edge of boundary layer
w	Wall
∞	Free stream

NOTE: This review collected figures from different publications to which the reader is encouraged to refer. Consequently, the notation therein was kept unchanged and any differences are defined in the text where the given figure is discussed.

SECTION I

INTRODUCTION

Broadly speaking the objectives of the study which led to the present report were to examine critically the available data on high-speed boundary layer transition to turbulence and to attempt to interpret the apparent agreements and contradictions within some rational framework which would not have to change with the acquisition of the next set of data. In particular, this framework should ultimately permit probability statements concerning transition in free flight on the basis of information from ground-based facilities. Special attention was to be paid to the cases of the more serious documentable discrepancies between reported results as touchstones of possible conceptual models. As expected, this focusing did lead to identification of a series of feasible experimental and theoretical programs, Section V, which would be likely to help resolve the discrepancies and provide decisions between competing concepts.

As part of this study, the author visited many laboratories and academic institutions and listened to discussions by many specialists interested in critical reappraisal of the high-speed transition evidence. There was near universal agreement that most of the information on high-speed transition, even in wind tunnels, was essentially so circumstantial (gross) that it was of little use for sorting out the superposed effects of the multiple parameters. Many experts called for extra care in future experiments, including <u>microscopic</u> identification of the disturbance environment and of the modes of transition. Hope was expressed that such microscopic experiments might establish a link between supersonic transition and supersonic stability (such as developed for flat plates by Mack in Ref. 1) and thus provide a basis for more rational usage of empirical correlations. The <u>macroscopic</u> empirical basis for the correlations and the prediction methods of transition used in industry was severely challenged with little hope offered for more solid evidence in the near future.

It seems worthwhile to convey here some of the pessimistic flavor of the conclusions by a few direct quotations. Prof. L. Lees opened one such discussion rather symbolically: "I think it might be appropriate to begin with a short prayer". A veteran experimentalist spoke candidly: "... Those of us who are operating wind tunnels have to look very seriously and ask questions on the measuring of the transition data that we have produced." ..."The questions of Mach number effect and unit Reynolds number effect, ... from the wind tunnel point of view are all up for grabs. We simply do not know what the magnitude is any more.... literal interpretation of the Pate-Schueler correlation (Ref. 2) would say that all

of the M effects and unit Re effects are really attributed to the noise radiated from the (supersonic) tunnel boundary layer. Our understanding of the ballistic range results of Potter (Ref. 3) contradict this...." Other experimentalists as well as theoreticians echoed these views of uncertainty as to the effects of the major parameters at supersonic and hypersonic speeds. Prof. Lees characterized the problem of using macroscopic measurements as follows: "It is like the problem of diagnosing a disease. You see you have a disease, you are sick, but you don't quite know why. You are confronted with a mass of data which people have tried very hard to correlate. But these macroscopic measurements often leave you more puzzled than enlightened because you don't really know what the mechanisms are behind the transition from laminar to turbulent flow at high speeds."

In view of such critical and self-critical assessments by many distinguished specialists, the prospective contents of the present report were revised. While the study of the available literature was comprehensive, (Ref. 1- 345) it made little sense to attempt a comprehensive compilation of the reported data - much of which has now been labeled as insufficiently documented. Instead, typical trends of results are illustrated for each group of similar experiments. In search for clues for ultimate deeper understanding the focus on the discrepancies between such groups of information is even sharper than originally planned. Much emphasis is placed on making the reader acquainted with conceptual mechanisms and models which could possibly reconcile the seeming contradictions. In particular, the possible or probable relationship between various highly idealized stability theories and ultimate transition to turbulence of the "real" boundary layer are described. The experiments with "microscopic" information play here a central role. And since much more is known about the correspondence between theory and experiments for low-speed boundary layers, this knowledge of the low-speed phenomena often serves as a point of departure for the presentation of the high-speed concepts.

Finally, in view of the controversial nature of the subject it is perhaps scientifically proper for the author to try to characterize at the outset his own possible predilections or experience biases. He has been concerned actively with various aspects of transition since 1948: as a hot-wire experimenter concerned with "microscopic" characterization of supersonic transition, as an interpreter of the coarser "macroscopic" experimental information, as a teacher of a course in stability theory, as a predictor in aerospace industry, and lately as a numerical analyst of special stability models at high and low speeds. Given a specific high-speed design with clear performance objectives he considers it a challenge to predict a probable range of location of transition on the basis of the weighted cumulative and latest information. However, especially after the recent critical

appraisals he would worry about the use of these same ad hoc prediction ranges by an uninitiated designer for a different design with different performance specifications. Time and again some of the implicit parameters are changed and the prediction bands may be rendered inapplicable to the new problem. They may tend to give an unwarranted sense of assurance and may thus even become misleading. Instability and runaway phenomena which are sensitive to multitudes of inadequately defined inputs are poor prediction risks. Hence there is discussion rather than recommendation of the various published prediction procedures in this review.

While the author shoulders the responsibility for any of the views and judgments in this review he did strive to establish whatever consensus could be achieved in 1968 as he took up the many controversial questions with one group of stability and transition researchers after another. It was an experience and an education. In fact, the report should list some ninety nine or more coauthors. Their collective experiences and wisdom permeate these pages as the reader can judge from the role played by the specific references. Special credit should go to the two dozen critics of the first draft of this review and to the obliging authors of the figures which put across many a subtle concept. The reader will find it rewarding to look up the original papers from which the illustrations were borrowed.

SECTION II

SOME LESSONS FROM HISTORY

After some sixty years of research on transition from laminar to turbulent shear layers a number of contradictions or paradoxes remain, even at low speeds, often glossed over and unexposed to the new generations of engineers and students of fluid flow. Simultaneously, the textbooks they read have failed to stress the capricious and snow-balling nature of this flow instability so that its implications to practical design are seldom appreciated. As the researcher and designer face extrapolation of transition information to combination of ranges of parameters not reachable in ground facilities in connection with entry at supercircular velocities and new expensive systems like the Scramjet, medium and larger lifting and non-lifting entry vehicles, hypersonic cruise and high L/D vehicles, etc. it is perhaps instructive to examine the ebbing tides of beliefs and research on transition.

The history of transition research is replete with examples of insufficient evidence leading to mistaken acceptance of partial truths as explanations of the total phenomenon and thus actually delaying further discoveries of its complexities. The transition pioneers were impressed by the three-dimensionality of turbulence and tended to take lightly any possible role of a two-dimensional amplification mechanism, hereafter called the T-S mechanism for Tollmien and Schlichting of Prandtl's school (see Section III). The high free-stream turbulence in wind tunnels of those earlier days indeed masked any such amplification so that its presence on a flat plate went unobserved.[1] Simultaneously, the fortuitous agreement of limited transition data, e.g. (Ref. 5), with Taylor's criterion based on the assumption of a local separation of the boundary layer induced by free-stream turbulence provided a sense of security for the three-dimensional view.

With the suppression of free-stream turbulence in the tunnel of the National Bureau of Standards, around 1940, Schubauer and Skramstad, (Ref. 6), in their classical and beautiful experiments verified the salient as well as many detailed features of the linear T-S eigenvalue oscillations of laminar layers on a flat plate. Their documentation and the independent verification by Liepmann, Ref. 7, was so complete that their signaling of the presence of substantial spanwise w' fluctuations (Liepmann's $w' \sim 2v'$ even in linear regime), which should not be present in two-dimensional flow fields, went unheeded for about a decade! Since total amplifications of disturbance amplitudes at a given

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[1] T-S amplification emerges from spectral analyses of layers in presence of as high as 0.42% free-stream turbulence - Bennett, Ref. 4. That it is essential (rather than incidental) to the transition mechanism in that case still remains an open question.

frequency by a factor of a thousand or more were observed, no need was seen for the powerful amplification by three-dimensional vortex stretching, and theoreticians and experimentalists alike were seeking non linear two-dimensional paths toward secondary instabilities and/or turbulent "bursts". Emmons' accidental discovery of sporadic formation of turbulent spots on running shallow water and his subsequent experiments verifying the wide generality of his observations, Ref. 8, brought to an abrupt end the self imposed myth of two-dimensionality and suddenly everybody was seeing spots even at supersonic speeds.

In time, largely through the research of Schubauer and Klebanoff turbulent spots and turbulent wedges were assigned a "terminal" role of conquering the neighboring laminar flow in a process beginning with linear T-S amplification, e.g. Ref. 9, 10. Their frequently nearly regular spanwise occurrence in low-disturbance facilities was traced to almost immeasurable spanwise disturbances which lead to differential growth of the mean laminar layer in so-called span-wise peaks and valleys, e.g. Ref. 9, with consequent span-wise maximized amplification and earliest local breakdown at the peaks (see p. 10). Criminale and Kovasznay, Ref. 11 and Brooke Benjamin, Ref. 12, further clarified the original Schubauer-Skramstead indications of two-dimensionality and demonstrated by Fourier syntheses of distributions of variously skewed T-S waves that localized areas of initially intensified disturbances should indeed develop with strong two-dimensional features in the linear regime even if their original spanwise to lengthwise extent were nearly unity.

This process of reconciliation between early T-S amplification and final spot genesis of turbulence was further reinforced by the documentation of parallel trends between T-S stabilization through cooling, suction, and acceleration (falling pressure) of the boundary layer and the increase in Reynolds number of transition, e.g. Refs. 13, 14,15, including the achievement of the spectacular value of 90 million on a cool cone flight, Ref. 16. Such encouraging verification of trends in overlapping research efforts apparently paved the way for the next costly lesson in dangers of overconfident extrapolation and one-track mindedness: the concentration of early intercontinental missile engineers on heat sink design. In the so-called blunt-body early transition paradox (not yet really clarified (!) but almost certainly pointing to non-uniqueness of transition behavior) transition on heat-sink noses was <u>not</u> delayed by the presumably strong favorable influences of cooling and of rapidly falling pressures. On the contrary, it often occurred at Reynolds numbers as low as 100 (based on momentum thickness) at which T-S waves would not even be amplified in the presumably less stable case of low-speed adiabatic flat plates, see Ref. 17.

In the late fifties the excessive dangerous confidence in the principal role of the 2D T-S type stability theory was similarly enhanced by the beautiful experiments on a flat plate at a Mach number of 2.2 of Laufer and Vrebalovich, Ref. 18. The fact that their experimental neutral amplification curve and dimensionless amplification coefficients could be correlated with those of Schubauer and Skramstad at M = 0 was impressive. Even the theoretical outer-layer fluctuation profiles appeared verified. After analyzing

the partial disagreement of their neutral curve with the results of various then available asymptotic theories, Mack concluded in Ref. 19: "The fault must lie with the theory" (but see Section III-4). In their scientific concern not to mix true data with qualitative observations, the authors did not mention that the beginning of transition sensed "microscopically" by a hot wire occurred at a rather low Reynolds number of about a million (based on length), for which the total T-S amplification did not exceed a factor of three so that the actual breakdown could hardly be ascribed to the two-dimensional T-S mechanism, present as it certainly was. In fact, two new competing, though related, modes of instability emerged from scientific semiconsciousness in mid-sixties with a claim of being primary theoretical suspects at medium and higher supersonic speeds (Refs. 20-24). Mack's computer discovery of a series of unstable modes (labeled "acoustic" by L. Lees) at supersonic speeds was greeted with a call for "agonizing reappraisal". While Dunn and Lin (Ref. 25) successfully impressed upon the public that in two-dimensional supersonic flows T-S waves with wave fronts oblique to the stream direction are less readily stabilized by cooling, their hint that they could be more unstable than their non-oblique counterparts even for adiabatic flows was not considered for a decade. Kendall's "microscopic" experiments (Ref. 22) confirmed quantitatively Mack's calculations for both the second 2D mode and the skew modes. At higher Mach numbers, theory and experiment show them to be more unstable than the 2D waves previously considered!

Competition between these multiple unstable linear modes - and perhaps some purely non linear ones, as yet not understood - can present situations in which the dominant roles can switch as the different parameters vary (usually simultaneously rather than singly). Could the current controversies concerning the effect of cooling (transition reversal) at Mach numbers past 5 and the unit Reynolds number effects be resolved by the possibility that the disharmonious results occur legitimately in different parts of the phase space of our parameters? It has been clarified once again (Refs. 2, 3) that the disturbance environment must be characterized as a set of parameters. Some may be subliminal with respect to our best sensing instruments (e.g. the 3D disturbances corrugating spanwise Klebanoff and Tidstrom's unstable boundary layer in Ref. 9, Fig. 4) but since they directly feed the runaway instability, they must be taken into account in any rational approach to design.

In the problems associated with the high-speed systems listed at the beginning of this section, there will occur additional parameters such as ablation and cross-flow, the role of which at supersonic speeds is virtually unknown, theoretically or experimentally. The richness of possible additional complexities and of interaction between parameters and mechanisms is almost discouraging. If these national objectives are to be spared the type of research shortsightedness detailed in this section, a more systematic cooperation (and constructive critique) between funding supervisors, theoreticians and experimentalists (across different, all too limited facilities) appears in order.

After such lofty sentiments it appears appropriate to return for perspective to the original 1883 laminar - turbulent transition of

Osborne Reynolds in a readily available facility - a circular pipe. A convincing explanation of the instability and transition remains lacking, though many have been offered. One of the latest by A. E. Gill (Ref. 26) proposes that the laminar profiles in pipes are seldom parabolic and describes a basic vorticity self-enhancement mechanism, feeding on the distortions from parabolic shape, that could lead to instability. The lessons one could draw from this article are (1) in searching for genesis of turbulence keep focusing on vorticity (2) don't forget that the real mean profile may be different than assumed, and (3) don't get discouraged about transition problems too early - they have a way of being around for decades.

SECTION III

ON THE NATURE OF RELATION OF INSTABILITIES TO TRANSITION[2]

1. LOW-SPEED MICROSCOPIC INFORMATION

One of the reasons why one might at first shy away from the Tollmien-Schlichting model is that the resulting orderly, cross-flow oriented unsteady vorticity pattern, $\omega_z(x, y, t)$, differs so markedly from the random unsteady three-dimensional mixture of vorticity components $\omega_x(x, y, z, t)$, $\omega_y(x, y, z, t)$ and $\omega_z(x, y, z, t)$ of the ultimately evolved turbulent boundary layer. Even the scale of the motion (or spectra) do not match. Thus Schubauer and Skramstad's ratio of (spontaneous, most amplified) T-S wavelengths to boundary layer thickness ranged from 8 to 9 (Figs. 13 and 27 of Ref. 6) whereas the larger energetic eddies in turbulent boundary layers range roughly between $\delta/3$ and 3δ (inference from latest presentations of A. A. Townsend and L. S. G. Kovasznay in Ref. 27). Such discrepancies suggest that a considerable three-dimensional reorganization including changes of scale - a secondary phenomenon or instability - must take place before self-sustained wall turbulence can evolve out of the orderly T-S motion.

On smooth flat surfaces with only mild 3D stimuli this role is apparently fulfilled by a small-aspect-ratio version of Greenspan-Benney time-dependent inflection instability (Ref. 35), documented by Hama and Nutant with the hydrogen-bubble technique (Ref. 36, especially) Figs. 13-15), Klebanoff et al (Refs. 9 and 38) and Kovasznay et al (Ref. 37), with hot-wire arrays and Knapp and Roache (Ref. 39), with smoke backed up with a hot wire. The artificially unstimulated three-dimensialization of Knapp and Roache along an ogive body, Fig. 1, is reasonably convincing of the overall linear and ultimately non linear geometrical features of transition. (Hama has demonstrated how careful aerodynamicists must be when they extrapolate their understanding of particle-type visualization, conditioned by steady-state experience, to interpretation of unsteady wave-like phenomena, Refs. 40-43, see also Ref. 266.) While their techniques, terminology and semantics differ (inflectional instability, spikes, hairpin eddies, Λ-shaped vorticity fields, primary Ω or milk-bottle vortex, snatched-away vortex rings, vortex-sheet kinks, slower-moving bumps, vortex trusses, spiraling vortices, Fig. 2, etc), these authors observed essentially complementary features and, most importantly, an onset of a smaller longitudinal scale on the order of 1/8 to 1/5 of the original T-S wavelength (i.e. δ to 2δ), a vertical scale of roughly $\delta/3$ to $\delta/2$ and of a comparable spanwise scale. Motion on these scales in presence of the reservoir of the large oriented vorticity of the mean boundary layer and of smaller residual randomness are expected to evolve rapidly into irregular three-dimensional motion - birth of a turbulent spot - through the now fully

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2. For deeper appreciation of this section familiarity with References 6, 9, 10, 28-38, 56 is recommended.

activated vorticity production rate

$$P = \vec{\omega} \cdot \operatorname{grad} \vec{V} \qquad (1)$$

without any further recognizable spectral breakdown stages. The commensurate time scales of this non linear development are generally on the order of one half of a T-S period or less and hence the events have been described as fast, rapid, or even explosive.

The differences in the evocative word-pictures of the above authors may reflect simply the difficulty of describing objectively three-dimensional vortex roll-ups and distortions. More likely, they stem from true differences in the detail phenomena represented mathematically in the complicated non linear terms of the convective derivative and of the production rate of vorticity, Eq. (1). As the scales and the degree of the three-dimensionality vary, its net contribution to spanwise transfer of fluctuating energy in the direction of the spanwise location of earliest breakdown, and its role in the vortex dynamics, must be expected to vary from one physical realization to another, stimulated or "natural". For example, the results of Tani and Komoda, Ref. 44, though less detailed, indicate clearly that an unexpected spanwise shift of the first breakdown position occurs when their three-dimensionality parameter is increased. This probably corresponds to a still more complex pattern of vorticity, judging by their measured phase distributions. By contrast, stimulation due to monochromatic sound (a small-amplitude irrotational velocity field which would not be expected to generate vorticity to first order) replaces the interlocking pattern of "vortex trusses" of Fig. 2 by alignments in rows and purifies the spectrum from random and neighboring components (Ref. 39 and 45). There exists strong evidence in the instabilities of shear layers (though unfortunately not a quantitative one in the case of attached boundary layers) that in the pre-breakdown non linear regime various modes of motion inhibit each other depending upon their relative strengths (e.g. theoretical contribution of J. T. Stuart and experimental contributions of A. Michalke and H. Sato in Ref. 27 and pp. 30-33 of Ref. 46).

The environmental three-dimensionality, the variable spectral content of free-stream disturbances and the rich-get-richer inhibition of the non linear behavior contraindicate the expectation of uniqueness in the transition phenomenon even for the rather well studied flat plates in aseptic wind tunnels at incompressible speeds. In fact, when Komoda increased his three-dimensionality parameter over that in Ref. 44, while the mean velocity profiles were still "<u>very close to Blasius</u>" (p. S88 of Ref. 47), his multiple hot-wire arrays revealed an entirely different pattern of scrambling of the vorticity before a turbulent spot was born - without indication of spikes, etc. The new pattern includes the development of an intense <u>vertical</u> shear

at a spanwise location between the so-called peak and valley[3] where eventually the turbulent spot is seeded. The thickness of the vertical "high vorticity layer" is again of the order of δ so that one could expect the turbulent self-regenerative processes to take hold at the high intensity levels measured by Komoda.

3. These describe spanwise locations by referring to high and low intensity of fluctuations as the three-dimensionality develops. The previously puzzling relation to the corresponding thickness of the mean boundary layer has been clarified by I. Tani's presentation in Ref. 27 or 56.

2. INVISCID LOW-AND HIGH-SPEED INSTABILITY AND TRANSITION.

In the incompressible attached boundary layers the instability is associated with the viscosity-controlled phase relations of the velocity fluctuations (Ref 48, pp. 59-66), a mechanism which apparently requires long wavelength-to-thickness ratios for amplification. In adverse pressure gradients, an inflection of the mean velocity profile develops and permits the inviscid mode of vorticity induction to enhance the instability (Ref. 48, 30,26). This can be seen from the broadening of the neutral stability loop in Fig. 3 (compiled from Ref. 49), from that of the Blasius profile to that of the mildly adverse Falkner-Skan $\beta = -0.05$ profile. However, the close similarity of behavior between the Blasius neutral curve and the amplification isoline $c_i = 0.01$ of the inflected profile indicates how strongly the higher amplification rates of the longer wavelength are still viscosity controlled when the inflection point is close to the constraining wall. The inviscid character comes into its own only in the regime of the shorter wavelengths[4] and higher Reynolds numbers between the curve segments B'C' and BC. As the boundary layer acquires more freedom from the wall constraint with increasingly negative β, the inviscid instability gradually takes over so that at the limiting separating-layer β of -0.1988 the maximum at A disappears and the horizontal asymptote BC reaches a level $\alpha_r\delta^*$ of 1.3 (Fig. 31 of Ref. 49). Simultaneously, the instability sets in at increasingly smaller Reynolds numbers and the rate of amplification increases rapidly at a fixed Re_{δ^*}.

Two considerations prompted the didactic digression to Fig. 3. First, wakes of thin two-dimensional streamlined bodies and two-dimensional jets also undergo inviscid instabilities with shorter wavelengths on the order of a characteristic shear-layer thickness or two. However, in these cases the larger-scale motions of the corresponding turbulent free shear layers match the scales of the inviscid instabilities quite well. Thus only a three-dimensionalization process need follow the non linear instability regime without dramatic changes of length and time scales. And since the hardly scientific characterization of "fast" transition really implies events more rapid than the original time scale, one should expect slow rather than fast transition to turbulence in two-dimensional jets and wakes. References 50 and 51 indeed comment on the contrast with the fast flat-plate transition and on the absence of "spikes and bursts". The constraint of the wall in attached boundary layers postpones the final three-dimensional reorganization to higher Reynolds numbers which generally allow finer-scale vorticity to develop (Lin. Ref. 52).

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[4] The natural T-S oscillations of Schubauer-Skramstad, Ref. 6, occurred near the letter B' in Fig. 3.

Clearly, there are other differences in simple free shear layers - the absence of the singular critical layer, the absence of the wall-anchored, high, mean-flow vorticity reservoir, the essential constancy of the Reynolds number based on wake width and velocity defect (which at lower Reynolds numbers may limit the instability development to the laminar non linear Karman vortex state) etc. However, when one is contemplating extrapolation of the overall stability and transition approach to supersonic and hypersonic Mach numbers the public surprise at not finding the plate-type transition in free flows perhaps holds a few lessons. For example, it underscores the help hypersonic transition studies could receive from a better knowledge of the final expected state of hypersonic turbulence. Furthermore, if the oblique T-S waves were indeed the most amplified, as mentioned at the end of Section II, the resulting skew unsteady vorticity strands (which in the linear range could criss-cross) would appear to be somewhat closer to the partly known structure of supersonic turbulence, Ref. 53. Possibly the transition development sequence might be abbreviated, requiring less total amplification through the T-S mechanism. These speculations have been influenced by the existence of shadowgraphs and schlieren photographs, unfortunately of irreproduceable quality, with skew, "rope-like" structure appearing in the visible meridian plane of bodies of revolution undergoing supersonic transition (e.g sketch in Ref. 105).

The second reason for inclusion of Fig. 3 is aimed at emphasizing some important contrasts and similarities between the low-speed inviscid instability and supersonic flat plate T-S instability. With rise in Mach number the variation of density across the layer assumes growing importance and the role of the low-speed inflection point is assumed by the point at which the derivative of $\rho dU/dy$ rather than that of dU/dy alone vanishes (Ref.1,20,54,55). Thus, compressible adiabatic flat-plate boundary layers assume increasingly more inviscidly unstable characteristics, until past a Mach number of approximately 3.5, they become inviscid in the sense described for the $\beta = -0.1988$ Falkner-Skan profile (see Fig. 17.2 of Mack's Ref. 1). In Fig. 4, borrowed from Mack, the wave numbers (non dimensionalized with $\sqrt{\frac{\nu_e x}{U_e}}$ rather than δ^*) obtained by setting viscosity to zero are entered at the right edge. The trends illustrate a smooth extrapolation to infinite Reynolds number at which the maximal amplification rates occur for truly inviscid behavior. It was the use of the inviscid equations as an exploratory tool that guided Mack through the at first baffling maze of intertwined characteristics hinted at by the merged regions in the upper part of Fig. 4, and led to the discovery of the more unstable second (acoustic) mode (for $M > 2.2$) and the other unstable higher modes (Refs. 20 and 1, Section 15).

Another similarity with Fig. 3 has occasionally deceived those who look only at neutral curves for guidance to stability and transition. The left-hand limit of the zero-amplification loop, i.e. the T-S critical Reynolds number short of which all infinitesimal disturbances

theoretically damp, decreases slightly with early rise in M and in inviscidness, as before. But the contrasting feature was found within the loop: the magnitudes or "hills and crests" of local rates of amplification (such as outlined by the isolines in Fig. 3) decreased as M and inviscidness increased. In fact, Fig. 5 (based largely on Mack's results) displays (a) the shifts of $Re_{x,cr}$ (based on distance from leading edge) for the two-dimensional compressible adiabatic flat-plate boundary layer, subjected to two-dimensional disturbances, and (b) the changes in the approximate, evolved total amplification of the most amplified frequency at Re_x of 2.25 millions, according to linearized instability theory. The ratio of the amplitude A at Re_x of 2.25 millions to that at $Re_{x,cr}$ drops rapidly from the thousand-fold value at low Mach numbers to the incredibly low value at M of 2.2 (for the conditions of the key Laufer-Vrebalovich experiments of Ref. 18) and then rise slightly, but not permanently, as the acoustic mode becomes more unstable than the first T-S mode.

The increasing stability of the boundary layer in the range up to M of 2.2 contrasts dramatically with the trend of transition Reynolds numbers of practically all available wind tunnel information. There, Re_{tr} on adiabatic flat plates decreases monotonically, levels off between M of 3 to 4 and then rises slowly before adiabatic experiments become impractical. The contrast is accentuated by the fact (Refs. 60, 113) that the normally detrimental free-stream wind-tunnel turbulence (vorticity) is suppressed by the increasingly large accelerations from the settling chamber to the test section. Indeed, at Mach numbers larger than 3 to 3.5, the transition location becomes insensitive to violent turbulence created on purpose in the settling chambers (Ref. 57-61).

Thus in the design range of the supersonic transport there are basic countertrends between stability theory and wind-tunnel transition behavior. Has transition switched to still different modes, namely the more amplified oblique Fourier waves, Refs. 21 and 23? Or to mechanisms hardly amenable to linear theory, such as that of lateral contamination or that operative in the early transition on blunt bodies (Section II)? Have the secondary processes (Section III -1) leading from the amplified, more inviscidly behaving, T-S waves to the final turbulence altered their character and possibly taken a "shortcut"? Or is the contrast brought about by a more severe acoustic disturbance environment in wind tunnels (Refs. 57, 62, 60) despite the alleviation from the effects of free-stream turbulence? See Section IV-2.

If there is to be a rational approach to design in this range of Mach numbers one must look to microscopic measurements (fortunately with proven techniques: Refs. 63, 64, 62, 18, 22, 65-67) to provide at least partial answers to these questions. Unfortunately, none of the numerous experimental stability and transition investigations to date, whether microscopic or not, have clarified these specific issues. Kendall (Ref. 22a and Section III-4) while successful in his amplification measurements of the second (acoustic) mode and of the oblique first mode at M of 4.5, ran into operational tunnel difficulties at

M of 2.4. He has been unable to verify his preliminary results and to continue his studies with turbulent noise radiation off and on for non-technical reasons. His techniques should be able to provide some of the above partial answers. Furthermore the Jet Propulsion Laboratories Supersonic Wind Tunnel has been the only one thus far in which the direct effects of the aforementioned severe acoustic environment could be assessed - see quotation from Kendall in Section IV-2.

3. PARAMETRIC TRENDS IN SUPERSONIC INSTABILITIES AND TRANSITION EVIDENCE

Analyses of instability in two-dimensional compressible "laminar mixing layers" (Lin, Ref. 52, Lessen et al, Refs. 68-69, Gropengiesser, Ref. 70) have predicted stabilizing trends similar to those of the first mode of the flat-plate boundary layer. Again, little attention was paid to the relatively larger supersonic instability of the three-dimensional or skew disturbances until the 1960's when Fejer and Miles (Ref. 71) demonstrated it for the degenerated case of a vortex sheet. Since separated laminar regions in front of control flaps and other protuberances will have to be provided for in design of supersonic and hypersonic vehicles, the possibility of (cooler) laminar rather than (hot) turbulent reattachment makes the above instability a most practical concern.

Researchers at NASA Ames Research Laboratories (Refs. 72-74) found that, contrary to the attached-layer case, Re_{tr} rises rapidly and monotonically at supersonic speeds in qualitative agreement with the theoretical stabilization trend - see Fig. 6, borrowed from Larson (Ref. 74). Near-wake experiments in Ref. 72 achieved Re_{tr} of axisymmetric mixing layers of 1 and 2 millions at Mach numbers of 4 and 4.5 respectively, indicating not only the continuation of the trend in Fig. 6 but transition Reynolds numbers only a factor of 2 or 3 below the flat plate or cone values. Presumably, all these flows are subjected to the same "spoiler" acoustic irradiation by the turbulence on the wind-tunnel sidewalls as are the attached layers of Section III-2. Is the mode or scale of the free-layer instability different and less susceptible to the tunnel disturbances? If one accepts a broad interpretation of Pate-Schueler correlations (Ref. 2; also Section IV-2) one would conclude that the presence of a unit-Reynolds-number effect in a transition experiment in a supersonic wind-tunnel constitutes evidence of response to the sound disturbances. Reference 74 displays a substantial Re/ft variation (logarithmic slope ~ 1/3) in its Fig. 7. So the spoiler seems to be present[5], yet the stability and transition trends agree. Clearly a good unanswered question, theoretically or experimentally, is: How would the offending irrotational sound field generate any of the T-S modes or lead directly to turbulent vorticity scrambling? The latter possibility is unlikely at subsonic speeds. It is probable that there are several mechanisms and that the subsonic effects mentioned in connection with Ref. 39 in Section III-1 and in Refs. 6 and 267 have little bearing on the present supersonic dilemma. See also Sections III-5 and IV-2.

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[5]Private communication from J. Kendall concerning a microscopically verified effect of side-wall sound on free-layer transition at supersonic speed states: "At M of 3.7 the wake of a thin plate remained laminar to downstream distances x > 27 inches, such that the overall amplification of the approximately most unstable frequency was about 10000 in the absence of turbulence sound (laminar sidewalls). With sidewalls turbulent, other conditions being unchanged, transition occurred at approximately 6 inches with an overall amplification of about 100". The amplification measurements are described in Ref. 22b. The cited magnitudes are thought provoking.

Moderate cooling of flat plates and cones at moderate supersonic speeds offers a similar instance of parallel trends between instability theory and occurrence of transition in the inclement wind-tunnel environment (e.g. Ref. 75-78). Figure 7, reproduced from Van Driest and Boison (Ref. 78), illustrates the magnitude of attainable effects even in presence of thin circular wire trippers, girding the 10° (total angle) cooled cone. The transition Reynolds number (based on the conditions at the edge of the boundary layer and on the distance from the nose) can grow three-fold even with a thin tripper. The indicated "complete stability" limit[6] should not be taken literally being based on an asymptotic theory inadequate at M of 2.7 (see Ref. 1).

With increased cooling, the boundary layer grows thinner and its inner portions acquire relatively more momentum so that a fixed protuberance becomes a more effective obstacle and the trend in transition may reverse as in Fig. 7. (In a companion figure Van Driest and Boison show that it takes much smaller isolated three-dimensional roughness to prevent the gains due to cooling, similarly to the 0.004 in tripper in Fig. 7.) This transition reversal represents an experimental illustration of the switching of dominant roles of two parameters (mentioned in Section II, page 6), which in this case occurs even when one of them, the dimensional roughness size, remains constant. However, by varying this parameter independently, the authors in effect mapped out a small neighborhood of a critical surface in the parameter phase space. In macroscopic experimental investigations of transition, focusing on such interchange boundaries between parameters, whenever they are encountered, provides extra depth of understanding, not otherwise achieved. Unfortunately, this boundary clarification remains inadequate with respect to the transition reversal (and rereversal) as more extreme cooling is applied on surfaces which are probably "smooth enough". See also Sections III-9 and IV-3.

Returning to moderate cooling without roughness, one would be encouraged by the qualitative agreement between the trends predicted by instability theory and transition behavior, if it were not for the puzzling opposite effect in Fig. 6. As Larson and Keating cool the wall (1) under the separated layer of (2) the upstream part of the body as well, transition

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[6] In a T_w/T_r (or T_w/T_e) vs. M plane, first-mode 2D T-S waves on a smooth flat plate are completely stabilized (quenched) in a region between the $T_w = 0$ axis and a hump-shaped "complete stabilization" curve. According to the Dunn-Lin asymptotic theory (Ref. 25) this curve starts at $M = 1$, $T_w = 0$, rises to a maximum at moderate supersonic speeds and recrosses the T_w axis between Mach 6 and 10, depending on the assumed variations of viscosity and heat conductivity with T. If the "exact" quenching curve had multiple crossings at a given M as T_w decreased, reversals and rereversals of quenching and amplification on a smooth plate would have to take place.

distance of the separated layer decreases and more so in the second case! One night's perusal of Gropengiesser's thesis manuscript, Ref. 70, indicates that at least the first effect has solid theoretical foundation, but a better assessment must await the availability of the thesis. Incidentally, Gropengiesser's analysis is of "spatial" type (wave number rather than frequency being complex) - the first at supersonic speeds. The similarity of its Mach number variations to those of Mack is then especially reassuring.

The examples in this subsection thus restore one's confidence that in many cases of supersonic transition the T-S instability theory may somehow describe the underlying mechanisms of the long build up of disturbances before the final non linear three-dimensional reorganization of the fluctuating fields. The highly mathematical nature of the theory (simpler as it is because of linearity) makes it difficult to identify the physical mechanisms. Even Mack speaks of "mystery lines" in the α vs. M plane (Ref. 1) which separate distinct behavior of solutions for the flat-plate problem. Since Brown (Ref. 23) and Mack (Refs. 1 and 20) have shown conclusively that at supersonic speeds one has to resort to numerical solutions while relying on the asymptotic theories for basic guidance, the numerical output resembles in a sense the outputs of carefully guided, repeated and rechecked sets of experiments. And yet the critical folding and branching of the solutions when one tries to imagine them in a suitable phase space of best-bet parameters is very elusive.

A chastening (or qualifying?) experience awaits the ambitious transition correlators should they embark on the important task of correlating the already preorganized information on the behavior of the most amplified disturbances as functions of M, Re, and cooling in Chapters 14 to 20 of Mack's opus, Ref. 1. Reshotko (Ref. 79) boldly shows the way by focusing on the controversy over transition sensitivity to cooling at higher Mach numbers (Refs. 80-84). He demonstrates that the absence or presence of the temperature effect in different hypersonic facilities may be reconcilable with the help of a Mack-based correlation and a number of plausible assumptions. In the language of this report, he shows that the measurements were carried out in different parts of the relevant phase space. The full validation of the Reshotko model would require fairly sophisticated experimentation. For the time being, Reshotko shifted the argument concerning hypersonic cooling from the dead center of YES or NO confrontations to the more fruitful consideration of the subtle relations between the underlying controllable parameters and those characterizing the disturbance environment. If this path proves successful, the designer will need more information on the disturbance environment throughout the operations of his vehicle.

4. SUPERSONIC MICROSCOPIC EVIDENCE AND VARIOUS INSTABILITY THEORIES

Each instability theory discards not only the terms of second order in the fluctuation amplitudes but also other selected terms considered to be of higher order for the objectives of the specific investigation. Mack and Brown have developed programs for the eighth order differential equation system needed to cover both the three-dimensional disturbances and the full viscosity effects, including linearized dissipation. Yet Mack's breakthrough utilized the simplicity of the second-order system to which the eighth order system reduces when the effects of molecular transport are neglected. One could ask: What features can one exclude in what range of parameters and still retain a reliable foundation?

One feature all the theories exclude is the variation of the properties of the external flow and of the boundary layer as the distance x from the leading edge increases. Thus the growing mean boundary layer at a given Re_x is approximated "locally" by a layer having the same U and ρ profile as a function of y, but not including their x derivative or their companion, the mean vertical component V(x,y). This assumption of locally constant base, historically misnamed as the quasi-parallel assumption, is generally considered satisfactory (Refs. 24, 85-92), except possibly for low Reynolds-number free shear layers and hypersonic attached boundary layers which thicken rapidly with M for a fixed Re_x. If one allows the x variations to enter more explicitly, the differential equations acquire x-dependent coefficients. Not only has one to deal with partial rather than ordinary differential equations but the generality of the approach to arbitrary disturbances by the combined eigenfunction expansion in y and Fourier decomposition in x and z vanishes, raising other serious questions. The preceding considerations introduce the problem raised by Brown (Ref. 23) when he decided to include the mean vertical velocity V(y) (while neglecting the x derivatives) in order to come closer to specific instability measurements.

Of course, even microscopic experiments contain inaccuracies and pockets of uncertainty. What constitutes solid evidence for what theoretical approximation? In view of the importance of establishing a rational basis for estimating transition trends, the present somewhat confused state of the evidence is here critically summarized - probably at the cost of a few old friendships. The present tentative probability assessments could well change should any of the experiments below, especially the fourth one be repeated.

The instability evidence of Brown and Mack rests on just four sets of microscopic experiments: two from the prehistoric era of supersonic two-dimensionality by Laufer and Vrebalovich (Ref. 18; M of 2.2 and 1.6) and by Demetriades (Ref. 93; M of 5.8) and two by Kendall. The first, K_1 at M of 4.5, is in Ref. 22a, while the second, K_2, at M of 2.4 was not published because a check of all relevant conditions could not be made. In view of the closing down of his facility and the improbability of a recheck, Dr. Kendall kindly

allowed the author to describe these very tentative results for the purposes of the present assessment. The L-V and D experiments suffered from sidewall sound contamination which called for generation of artificial "siren" type disturbances somewhat larger than otherwise necessary, especially in case D. By contrast, Kendall's difficulty in K_2 was associated with separation at the back of his test plate, his wall boundary layers remaining laminar. While attempts at minimizing the effects of this separation consumed time, the condition probably did not influence the key 2D glow-discharge excited measurements. However, not all supporting information could be checked and the rigorous Laufer-Kendall tradition of JPL (see p. 279 of Ref. 18) frowns on publication of unchecked data. Thus, the purest touch stone of instability theories consists of the K_1 measurements of the first and second modes in Ref. 22a.

For the sake of clarity, a number of ordered independent observations can first be made.

(a). Both Brown (Ref. 23, p. 1758, line 4) and Mack agree on the neutral curve at M of 2.2 for 2D disturbances, labeled "Complete Equations, Numerical Solutions" in Fig. 8. Thus fortunately there is a common point of departure which precludes any numerical error as an explanation for the difference between this neutral curve and the L-V data in Fig. 8. Furthermore, any disagreement between the results from their respective 8th order systems probably stems from the extra V(y) and dV/dy mean velocity terms of Brown (although differences in handling 3D disturbances may also enter).

(b) The agreement between the all-important K_1 detailed measurements and Mack's theory for both modes 1 and 2 including amplification rates and phase velocities is simply remarkable - see Ref. 22a and Figs. 20.3 to 20.5 of Ref. 1, the first of which is reproduced here as Fig. 9. The evidence is thus very strong that at M of 4.5 Mack's system provides an excellent base for the linear development of disturbances on their road toward transition. The qualitative agreements between theory and transition, cited in Section III-3, are then probably not fortuitous. Of course, the reasons for any exceptions, such as those in Section III-2, must be closely examined to preclude overconfidence in any range of parameters. On the other hand, the promise of at least a partial rational tool appears to be sufficiently great to warrant early <u>extensions</u> of the <u>theory</u> to supersonic flows with <u>pressure gradients</u>, to flows with <u>ablation</u>, and to <u>three-dimensional flows</u> (which all are practically important, and the latter two prime suspects in hastening transition). At the present time there exists no <u>supersonic rational guide</u>, even inviscid, <u>with respect to these parameters</u>.

(c) Brown and the present author agree that the arrangement of seven spanwise separate slits for the generation of artificial disturbances in D undoubtedly caused a complicated single-frequency mixture of two and three-dimensional disturbances (which at the time were not generally recognized as serious). The special care with which the search for a neutral curve has

to be conducted is illustrated on pages 279-282 of L-V (Laufer-Vrebalovich). No comparable precautions are indicated in Ref. 93. With the additional problem of the sensitivity of the hot wire with respect to the phased superposition of signals at different orientations with different rates of growth and decay, the neutral curve D can hardly have the meaning assigned to it by Brown. Furthermore, according to Ref. 93:..."The air injection rate may be .... affecting the fluctuation amplitude and also changing the boundary-layer thickness. Both of these effects are thought to be small". The injection rates were not very small and varied from point to point: "Generally, data were taken at all subcritical rates, the guiding consideration being the appearance and clarity of the energy peak at the siren frequency". Laufer and Vrebalovich on the other hand tried to measure the mean layer properties, pp. 271-272, and identified the danger of interaction between the disturbances and the mean flow field (their Fig. 21 and pages 277-278). They speak of "the extreme sensitivity of the boundary-layer stability mechanisms (and incidentally of the instrumentation) to any changes in the mean flow field".

(d) In view of these different considerations, it would appear that Brown's computations at M of 5 would be more suitably tested against the clean K_1 results at M of 4.5 rather than the obscure results D at M of 5.8. As basic a question as that of the inclusion of V(y) should be decided on the basis of the most reliable information. It is evident from the date of the contract report in Ref. 23 that Kendall's results were not in existence when Brown made his computations. The author has therefore inserted Brown's neutral points for a 55° oblique wave (Brown's Fig. 6) into Fig. 9. The comparison does not speak well for the inclusion of V(y) into the system of the equations even when allowance is made for the shift of Mach number from 5 to 4.5. It is hoped that Brown's program can be used for a complete check of K_1 results, including amplifications and phase velocities.

(e) Brown's present results have disclosed the sensitivity of the stability characteristics to the inclusion of V(y) and dV/dy at M of 5. However, since $\partial U/\partial x$ and $\partial \rho/\partial x$ are not included (for the mathematical reasons discussed earlier) the equation of continuity of the mean flow is not satisfied. It has been the author's experience that in problems involving vorticity and entropy perturbations, which tend to be mass attached, approximations involving violations of mass conservations are usually coupled with spurious sources of vorticity and entropy fluctuations. This may be one of the reasons for the discrepancy between Brown and Kendall. As much as the increase in V in hypersonic problems is disturbing, Brown's approach appears contraindicated on the basis of present information.

(f) According to Mack's inviscid and viscous results (Ref. 1, Section 15) the region of the L-V and K_2 experiments near M = 2 is peculiarly sensitive to changes in mean U and ρ profiles, and hence to obliquity of the waves, heat transfer and even static temperature level. It is possible that in this "singular" region inadequacies of the theory (e.g. the omission

of the V terms) might cause larger errors than at $M = 4.5$ - see item (b). A measure of the discrepancy between L-V and Mack-Brown at $M = 2.2$ (see item (a)) is the shift in the neutral curve in Fig. 8. Both branches of the K_2 (unchecked) neutral curve are higher than the L-V data in Fig. 8 for $R < 580$ and rise rapidly as R drops below 500. K_2 waves were verified as two-dimensional while some doubts exist about the L-V experiments - see items (g) and (h). Both Brown (Fig. 3 and 5 of Ref. 23) and Mack (Fig. 20.1 and 20.2 of Ref. 1) "perturbed" the mean 2D flows at M of 2.2 by including 3D disturbances and Brown by including the V terms as well. From a comparison between these figures it seems that (1) at M of 2.2 the sensitivity to the V effect is much smaller than at 4.5 (2) the L-V results would agree with the theories quite well if the experimental disturbances were sufficiently oblique, on the order of 55-60° - see item (g).

(g) As previously mentioned the L-V experiments were carried out before the possible role of the 3D disturbances became evident. Checks on two-dimensionality of the disturbances and mean boundary layer were apparently omitted. The original 1958 JPL Report No. 20-116 discloses that the span-wise slit for the siren excitation was only 1.5 inches long compared to a 10 inch operating distance and to wavelengths on the order of 0.7 inch. Kendall's adverse experience with warping of two-dimensionally excited disturbances at M of 4.5 (where their theoretical amplification relative to skew disturbances is larger than at M of 2.2) might suggest that a mixture of 2D and skew disturbances could have been similarly present in the L-V experiments.

(h) However, the 2D part of the incomplete K_2 experiments at M of 2.4 also disagrees with the 2D theory concerning the location of the neutral points and the measured amplification rates which reach some 60% of the L-V values at $R = 500$. Both the waves and the mean boundary layer were checked for two-dimensionality. Furthermore, at any wire overheat, the fluctuation amplitudes through the boundary layer thickness were self-similar at different x positions, indicating a pure signal. (The self-similarity was marred in the L-V experiments.) Unfortunately, there was no opportunity for absolute measurements of the mean U and ρ profiles with the glow-discharge excitor operating. (There was a 2% outward shift in the relative ρU measurements with the glow-discharge on even though the artificial disturbance level was an order of magnitude smaller than for L-V). In this very sensitive Mach number region (see item (f)) one must know whether these profiles matched the theoretical mean profiles for which the stability characteristics were computed.

(i) One can offer the following <u>tentative conclusions</u>. It is highly desirable to repeat and complete Kendall's experiments K_2 in order to remove the slight element of doubt about the theory in that sensitive Mach number region. In the meantime, observations (f) to (h) suggest that the partially unknown conditions in the experiments L-V and K_2 may also be responsible for the existing discrepancies in this Mach number range. They may all be consistent, simply referring to different mean flow conditions. Observations (b) to (f) indicate that the inclusion of V and dV/dy in the theory without simultaneous (prohibitive) consideration of the x variation of the mean flow is less likely to be correct than the quasi-parallel theory.

It appears that the programs of Mack and Brown (less the V terms) do represent a promising rational guide to the parametric trends of the linear part of the development of turbulence. Thus the recommendations for extension of the system to the three practically important parameters listed under (b) deserve early attention.

It is hoped that the present subsection will be accepted in a constructive spirit and that it will help the uninitiated to appreciate further the subtleties of the theoretical and experimental problems at supersonic speeds. (How important it is to know well the actual mean profile and how often is it really known in nonmicroscopic experiments?) As a reminder of the richness of possible combinations of effects - without cooling, roughness, non linear developments, pressure gradients, cross-flows, etc. Figure 10 is reproduced from Ref. 1. Of course it is the cumulative effect of these different local amplification rates along the growing boundary layer which would ultimately lead to non linearity and breakdown.

5. INSTABILITY THEORY, NON-SIMILARITY OF BOUNDARY LAYER, AND EFFECTS OF UNIT-REYNOLDS NUMBER.

In order to appreciate better the possible degrees of interrelationship between non similarity due to roughness and linear instability characteristics one resorts again to low speeds where recent microscopic experiments have disclosed the existence of several mechanisms. The simplest situation is that of a single two-dimensional roughness (e.g. a wire of height $k < \delta$, attached to the wall at distance x_k from the leading edge of a flat plate) which has been studied by P. Klebanoff (Ref. 94) in the fundamentalist Dryden-Schubauer-Klebanoff tradition. Two-dimensionality of the basic Blasius layer at x_k and of the roughness was established within the accuracy of careful measurements. However, significant spanwise variations of fluctuation velocity u' sensed by a hot-wire were observed downstream of the roughness. The first lesson (supported by evidence elsewhere) thus appears to be that even carefully installed two-dimensional objects generating longitudinal pressure gradients (this includes leading and trailing edges) enhance three-dimensionality of amplified disturbances. The spanwise locations of the (intensity) peak and valley (see footnote on last page of Section III-1) remained unchanged downstream. The three-dimensionalization undoubtedly accelerates the approach to turbulence as discussed in Section III-1.

By tracing the development of the fluctuation spectra from the locally separated velocity profiles to the reattached non-similar profiles and finally to the reestablished Blasius profiles and comparing them among themselves and with theoretical amplification rates, Klebanoff observed (a) that a T-S amplification mechanism corresponding to the <u>deformed</u> profiles dominated the development and (b) that free-stream turbulence partly penerates and agitates the boundary layer (the motions remaining uncorrelated with T-S waves of the same frequency) and partly evokes independent amplifying T-S fluctuations.

Some of the observations agree with and extend the results of the earlier hot-wire explorations of Tani and Sato, Ref. 131. The roughness in effect operated like a series-inserted, powerful amplifier with a broader bandwidth (see also Fig. 3). As the unit Reynolds number changed, the bandwidth and the amplification "setting" varied. At high unit Reynolds numbers, turbulence could spring forth in the "recovery zone" before the Blasius profile reestablished itself. At somewhat lower unit Reynolds numbers, the distorted profiles merely passed on to the less-amplifying normal profiles <u>new</u>, higher and broader, disturbance spectra. For fluctuation levels below about 1% of free-stream velocity, the preamplified parts of the spectra to which the reestablished profiles were T-S sensitive, would then grow still further, leading to an earlier-than-normal transition. The role and sensitivity of the preamplifier is illustrated by a 70% rise of the (beginning) transition Reynolds number from 4.15×10^5 to 6×10^5 as the Reynolds number per foot was lowered by 14% from 1.16×10^5 to 10^5.

Parenthetically, "the unit-Reynolds-number effect" is no stranger to low-speed facilities, but one can decrease the mystery by tracing the changes in the intensity and spectra of the free-stream disturbances, which make up a part of the effect, e.g. Kuethe, Willmarth, and Crocker, Ref. 95. One notices that Klebanoff has a "transition reversal" due to roughness with unit Reynolds number as parameter while Fig. 7 demonstrated a "transition reversal" due to roughness with wall temperature as parameter at M of 2.7. Of course, wall cooling increases the unit Reynolds number in the boundary layer in which the roughness is placed.

Another way of looking at the phenomenon is to recognize that one deals with an x-dependent pressure field in the vicinity of the roughness (or an x-dependent departure of the geometrical similarity of the boundary) which causes a change in the mean boundary layer profile. As unit Reynolds number or wall temperature increase, the amplification processes set in at a smaller x while the location of the non-similar feature remains fixed. Disturbances thus have different histories as they grow from some free-stream inoculated seed into a wave-packet while traveling downstream at presumably the T-S group velocity. Irrespective of the sensitivities of the subsequent non linear developments, the linear part of the disturbance growth depends on the integrated history along the wave-packet trajectory. Only if the boundary layer is completely self-similar can the ratio of the amplitudes A/A_1 of Fig. 5 scale as a function of a single Reynolds number.

Most practical vehicles and even simplest wind-tunnel models do not have self-similar boundary layers all along their relevant T-S sensitive lengths. Any departure from similarity of the boundary layer will in principle bring about a unit Re effect into the A/A_1 function as Reynolds number based on δ changes. Sometimes "practically" insignificant regions of geometrical non similarity cause substantial unit Re effects. Thus, the discovery of the powerful influence which small degrees of blunting of leading edges (noses) have on the x location of transition on supersonic flat plates (cones) occasioned a surprise and a controversy in 1952-56 (Refs. 96-105, 77). Such blunting indeed causes x pressure dependence extending downstream only over distances commensurate with the diameter of the blunting, but through the detached shock wave it also generates an entropy layer of commensurate thickness. Not until this entropy distribution (traveling along streamlines with little diffusion) becomes swallowed and digested by the boundary layer, which grows into it, will the T-S amplification rates be characterized by the local Re_δ. Even then, Re_δ will differ from that which would theoretically occur at the same x without blunting. The computation of the "swallowing distance" involves rather complicated viscous and inviscid flow fields so that various approximations, not all harmonious are used, Refs. 106-110. Some scatter between reported results can be expected on this account and because of inaccuracies in the none-too-easy measurements of the blunting. Furthermore, manufacturing and maintaining of spanwise uniform thicknesses on the order of one thousandth of an inch presents non-trivial problems in

model technology. The practice of using several thicknesses and extrapolating Re_{tr} to zero thickness seems generally accepted, e.g. Ref. 2. The complexity of the cooperating effects can be seen from the fact that the Reynolds number of transition obtained by such a limiting procedure generally remains a function of the unit Reynolds number in wind tunnels. It is to this residual unit Re effect that Reference 2 addresses itself.

The departure from similarity of the boundary layer can come not only from the x variation in free-stream characteristics, $J_e(x)$, $p_e(x)$ and $S_e(x)$, but also from x variation of the wall parameters determining boundary conditions, $T_w(x)$ and $\dot{m}(x)$. Suspecting that the parabolic downstream influence of such variations may be extensive, J. Whitfield (Ref. 111) generated Fig 11. An idealized step-wise case of a "hot" leading edge at a Mach number of 6, simulating experimental conditions in wind tunnels and free flight (see for instance the milder case of Fig. 11 of Ref. 83), was computed with the aid of the Jaffe, Lind, and Smith program for non similar boundary layers, Ref. 112, with thought-provoking results. In the upper part of Figure 11, the computed intermediate mass-flux profile (at a distance x' from the cold junction equal to 147 times the thickness of the boundary layer at the junction) can be compared with the asymptotic profiles over the leading edge (at the "hot" wall-to-stagnation temperature ratio of 0.8) and that far downstream, corresponding the "cooled" 0.2 value of the same ratio. From the lower half of Fig. 11, one observes that the profile adjustment (defined immediately above the figure) is less than 70% complete!

The question of the true significance of such changes in the profile will remain open for some time because profile dependence on x is presently beyond the capability of reliable instability theory - see beginning of Section III-4. Adopting the approximation of locally constant base one can turn to Mack's cooled plate results at M of 5.8 Fig. 12, as a guide. Keeping in mind that the ordinate is proportional to the exponent in an exponential growth, one can see that the local heating of the leading edge could act as a powerful preamplifier like the single roughness of Klebanoff - if the environment harbors disturbances with affinity for T-S mode. In that mode the oblique family could possibly fatten up beyond linear recall before the wall quenching would become operative. On the other hand, the hot lip would tend to stabilize any "acoustic" modes, in particular the most dangerous mode 2. Because of the competing modes the situation looms again more complex than it is at low speeds even when no account is taken of the influences of mean cross flow and other, strictly non T-S modes. Furthermore, it is to be expected that as the unit Reynolds number varies, the preamplifier (or quenching filter) will influence different segments of the amplification history of a wave packet relative to a fixed hot-cold junction. Actually the latter would be modified as well since it simulates the balance between the aerodynamic convective heating and conductive heating inside the body. Nevertheless, hot lips and hot noses make good candidates for sponsors of unit Reynolds number effects. The unanswered question is: how large can this effect be?

As already mentioned, non uniformities in leading edges and noses bring about x and z (or θ) dependence. Through the influence on the mean boundary layer the combined effects tend to linger downstream as the author was able to trace with the aid of a hot wire and pitot tube at $M = 1.77$ (Ref. 113). Extensive research on supersonic transition in a combination of tunnel and aeroballistic range at Ames Laboratories has pinpointed the sharp lip or nose region as one of large sensitivity to minute 3D roughness and imperfections on colder bodies especially at higher unit Reynolds numbers, see Jedlicka, Wilkins, and Seiff (Ref. 114), Carros (Ref. 115), and James (Ref. 116). In the author's 1.77 M experience, the absence of any higher-intensity disturbances until near the downstream location of transition, indicates a possible T-S mechanism enhanced by the three-dimensionality (see the end of this Subsection for documentation of such behavior at low speeds). The Ames phenomena may or may not have bypassed the T-S mechanism (Section III-6) - a possibility of concern in any new range of parameters.

The hot-lip example focuses attention on two rather neglected problems especially at high speeds:

(A) Determination of environmental disturbances for different facilities and testing techniques;

(B) Assessment of receptivity of the boundary layer to such disturbances.

The latter concern was dramatically illustrated by G. B. Brown in 1935 (Ref. 117) when he demonstrated complete immunity of a low-speed 2D jet to sound irradiation of the dangerous frequency until the sound was allowed to penetrate laterally to the root of the jet at the orifice itself. Apparently the jet vorticity layer could not assimilate the irrotational excitation except in a more singular region of detachment from the solid boundary. Receptivity to sound through singular regions near stagnation points, separation points, etc. may be of lesser importance at supersonic speeds because of changes in relative propagation speeds of the T-S waves and sound.

In one view the response of a boundary layer in the T-S sense thus depends not only on the presence of identified potential contaminants in the free stream but also on some kind of transfer functions characterizing the assimilation of the free-stream disturbance packets into "initial space-time distributions" inside the layer[7] from

7. At higher supersonic speeds the development of a disturbance can depend quite drastically upon the location at which it is "internalized" by the boundary layer as Mack has shown in connection with cooling effects at M of 5.8 and Fig. 12 of Ref. 20. History of the disturbances thus matters in many ways.

which they can grow according to spatial or temporal instability theory, see (b) p. 23. In another view, the eigenvalue problem would be replaced by obtaining direct response functions to free-stream fluctuating fields from non-homogeneous disturbance equations. This forcing approach was abandoned in the 1950's and is currently in the early stages of reconsideration, Refs. 118 and 119. Physically, one difficulty stems from the differences in the intrinsic propagation speeds of the free stream disturbances and those of the most excitable T-S waves. In either view, the relationship between measured free-stream disturbances and amplification of disturbances in the boundary layer is indirect. See also observation (b) p. 23.

As to (A), the presence of multiple 2D and 3D instability modes suggests that adequate characterization of the disturbances should include that of the three-dimensional orientation besides the intensity and spectral measurements. Separation into vorticity, sound, and entropy modes (Refs. 64, 62, 60, 113) appears desirable even in low-speed wind tunnels. In fact, there are indications that larger-scale unsteady "incompressible" pressure fields may be causing much of the damage; e.g. compare Refs. 120, 121 and 122. Only microscopic diagnostic measurements in the free stream with simultaneous microscopic probing of the boundary-layer response can clarify the roles of turbulence, progressive and standing sound waves in Ref. 267. At supersonic and hypersonic speeds, one may have to be satisfied with partial, hopefully illuminating, answers because of considerable technical difficulties, Ref. 62. Currently, funding difficulties have cut off some promising response explorations by Kendall in the Jet Propulsion Laboratories Supersonic Wind Tunnel, the only ones of their kind.

Earlier in this section, the ratio of disturbance amplitudes, A/A_1, at two stations, was seen to scale with a single Reynolds number only when the boundary layer is completely self-similar (and the assumption of locally constant base is justified). Steady perturbations of geometry, free-stream, and boundary conditions could each induce a non similarity which would in effect make A/A_1 dependent on unit Reynolds number. Now, the environmental disturbances (A) (especially in wind tunnels) and the boundary-layer receptivity (B) to these disturbances also depend upon many parameters, in particular Mach number and Reynolds number, often in a complex manner (Ref. 57 and 60). As a simplest example, consider the spectrum of sound radiated by the turbulent boundary layer on the sidewall. In all probability, the frequencies in the energetic part of the spectrum will vary inversely with the boundary layer thickness even at hypersonic Mach numbers (Ref. 123 and 124). If so, one has a picture of the likely shift in the most energetic frequencies of a class of important environmental disturbances with M and unit Reynolds number. The non-flatness of the disturbance spectrum and its shift with unit Reynolds number must be grafted upon the A/A_1 function of the parameters. The dependence of the intensity of the disturbances can be expected to be at least as complicated.

One might say that it would be most surprising if the disturbance amplitudes emerging from the linear T-S regime were independent of unit Reynolds number when these various influences operate together. Even when only the linear T-S mechanism is considered one may safely assert that the unit Reynolds number effect does not represent one effect but a complex superposition of many functional relationships, not all of which have been mentioned. In some ranges of parameters one simpler combination of influences may dominate and deceptively regular dependence on the dimensional ignorance parameter, the unit Reynolds number, may result. The danger perhaps lies in thinking this regular dependence too general. As two given families of experiments thread their way through the range of instability characteristics, partly portrayed in Figs. 10 and 12, in presence of their inherent non similarity parameters and variable environmental inputs (A) and (B), the disturbance outputs may vary in parallel over a range of parameters and then part company.

Such changes are observed but often readily forgotten or dismissed as "bad points". The most recent surprise was experienced by Softley et al (Ref. 109) when the Mach number 8-9 results failed to follow the anticipated 0.3-0.4 power variation with unit Reynolds number and the Reynolds number of transition on their 10° total-angle cone remained essentially constant, see Fig. 13. Actually, one might say that such changes in the dependence on the ignorance parameter are to be welcomed because they provide an opportunity of removing part of the ignorance by studying more carefully the response to different controllable disturbance and shape parameters in the vicinity of the conditions where the change of character took place. Systematic exploitation of such spoiler techniques for sensitivity to isolatable parameters can add considerably to the depth of understanding which is possible in non microscopic experiments.

It is appropriate to end this Subsection, heavy with speculation and exhortation, by returning to the reality of microscopic low-speed observations. In 1961-62 Tani and co-workers (Ref. 125) focused on the far-downstream development of the steady and unsteady wakes behind a single three-dimensional roughness, namely a vertical cylinder 2mm in diameter, protruding 2 mm (k) outward from a flat plate (x_k of 0.4m and U_e of 6.6 m/sec.). When the near wake (the equivalent of Klebanoff's region of non similar profiles, p. 21) settled down (see also Section III-6) a spanwise corrugation of the mean boundary layer remained. (It had a nearly constant width which scaled with k.) The steady horseshoe vortex anchored in front of the roughness caused a downwash in the wake center, making the boundary layer there 15-20% thinner than normal. Nevertheless, past the near wake, the mean profile there and elsewhere agreed with the Blasius profile within the accuracy of the measurements. Laterally moving hot wires disclosed thicker symmetric ridges on the two sides of the wake, then a symmetric thinning of the layer, before the undisturbed state was asymptotically reached. The fluctuation response to a mild stimulation from a vibrating ribbon followed the exponential law of T-S waves and the profiles

remained Blasius-like until the non linear regime set in. At a given height the wires recorded higher fluctuating as well as mean velocities at the extra thin central section and at the two thinner-than-normal sidebands. The development thus resembled the normal T-S peak and valley pattern (see references cited in Section III-1 on p. 8 and footnote 3 on p. 10) in spite of the upstream wounding of the boundary layer by the roughness. However, as the non linearity approached, the maximum amplification occurred not in the center but in the thinner sideband where also the first breakdown took place. This unexpected behavior is now suspected to be due to the difference in the a.c. energy transfer in the spanwise direction - see Tani in footnote 3 on p. 10.

These careful experiments demonstrate that in the so-called subcritical regime the isolated 3D roughness plays a variant of the role described for the 2D single roughness of Klebanoff at the beginning of this Subsection. It may not preamplify as much as the 2D roughness, but it fosters a much stronger spanwise non uniformity of the mean layer. The normal T-S mechanism enhanced by the spanwise corrugation (Refs. 9, 36-38)"feeds"on free-stream disturbances, preamplified or not, and brings about an earlier than normal non linearity and breakdown. This constitutes a subtle far-wake cooperation between the parameters of the 3D roughness and those of the T-S mechanism. Like the Klebanoff's case this cooperation can hardly be expected to scale with pure Re_δ (even if the disturbances were truly invariant) because there are at least two other characteristic lengths besides δ, namely x_k and k. The transition Reynolds number indeed varies with the catch-all unit Reynolds number when a single 3D roughness is present and does so differently than when the latter is absent. At a certain stage when the unit Reynolds number increases, transition moves rapidly forward to the near wake of the roughness. The role of the near wake is taken up in the next Section.

6. SINGLE 3D ROUGHNESS, T-S BYPASS, AND CRITERIA FOR SELF-REGENERATION OF WALL TURBULENCE.

At higher unit Reynolds numbers (or presumably at higher excitations), breakdown and transition in Klebanoff's 2D roughness experiments (Section III-5, p. 23) would occur in the non similar recovery zone or even over the locally-separated flow region. The preamplifier of the distorted mean layer would drive the level all the way to the non linear regime and preempt the normal T-S processes in the Blasius layer. In view of the features in Fig. 3 this distinction between degrees of T-S type amplification would probably not be worth making if it were not for the contrast with the disturbance behavior in the near wake of an isolated 3D roughness. Unsteady visualizations and hot-wire measurements of many authors (Refs. 34, 125-129) captured various phases of the qualitatively different phenomena like that of Fig. 14 (reproduced from G. R. Hall's Ref. 130).

In Fig. 14 the horizontal cylindrical obstacle is burried deep in the boundary layer only the inner portion of which is made visible by smoke. Keeping in mind that roughness is time-independent and passive, one can surmise that the near-wake preamplifier had affinity for a portion of the spectral distribution of the fluctuations present near the wall, however small. In fact, it selected a wave pattern and drove it to the non linear regime as the vortex formation and motion in Fig. 14 documents. However, in contrast to Fig. 2, there were no "bursts" and the flow remained laminar! These non linear vorticity formations simply diffused as they moved downstream toward the far wake (discussed at the end of Section III-5). The unstable vorticity formations behind roughness elements can take diverse and intriguing shapes especially if there is spanwise asymmetry. For their vertically oriented cylindrical element, Tani et al describe the formations as "a pair of closely spaced vortex filaments originating from spiral filaments which rise vertically from points on the plate right behind the roughness element" in Ref. 125. These also decayed, leaving only the anchored horseshoe vortex pair responsible for the spanwise corrugation (end of Section III-5).

Thus, in the subcritical regime of a single roughness there may often be much vigorous unsteady three-dimensional vortical activity which fails to trigger further scrambling of the neighboring reservoir of oriented vorticity ω_z and to sustain wall turbulence. This occurs in spite of the fact that the scales of these disturbances are closer to the anticipated scales of the energetic turbulent eddies than are the scales of the T-S motion (see discussion at the beginning of Section III-1). Either these scales are too small (too diffusive), or the intensity is not high enough, or both. The smallness of these scales probably explains why the Tani-documented roughness effect took the subtle indirect path through three-dimensionalization of the mean flow rather than the direct "feeding" of T-S instability as in Klebanoff's 2D broad-band preamplifier (Section III-5: (b) of p. 23 and pp. 28-29). This lower "effectiveness" of the 3D roughness at low speeds had drawn many comments in the literature.

Viewed from this perspective, the passive single roughness provides too restrictive an input of disturbances for adequate parametric exploitation of the elusive criteria of initiation of self-regenerative wall turbulence and of its minimum Reynolds number. A microscopic investigation based on various three-dimensional disturbances, controlled in frequency and amplitude, would appear as a fruitful next step at "incompressible" speeds. Design of appropriate disturber units is now under way at the Illinois Institute of Technology. Parenthetically, the six narrow slits of Demetriades' intermittent siren at Mach number of 5.8 (page 18 and Section III-4-c) represented in fact a collection of such controlled 3D disturbers rather than an operational equivalent of a two-dimensional vibrating ribbon.

As many observers of 3D roughness effects have well documented (e.g. Refs. 125-134, 137, 138 and references therein), at some stage of the development "the slightest increase in stream velocity or roughness height changes the pattern from twin streaks to a fully turbulent wedge originating at the roughness element. This quick movement of transition position seems to distinguish the effect of 3D roughness from that of 2D roughness ..."(Tani, Ref. 133). The key to this part of the contrast of the behavior of critical Reynolds number Re_k probably rests on the fact that the unsteady vortical formations, like those of Fig. 14, now do change to turbulent eddies, initially on the order of the scales characteristic of the roughness wake (e.g. Fig. 11 of Ref. 130). The T-S mechanism of the whole layer and its long waves have been bypassed. Rather, the near-wake instability apparently can feed directly into the vortical motion which constitutes self-sustaining turbulence in a widening turbulent wedge. The rapid acquisition of randomness and other scale sizes in this area has not been investigated in detail, but it can be inferred from isolated evidence.

While the scales of the 3D vortical motions apparently must be in the proper range, their intensity undoubtedly plays a role in the self-regeneration criteria. By studying the turbulent breakdown in a laminar layer disturbed by increasingly strong spark discharges, Elder (Ref. 139) came to the rather strong conclusion that whenever the streamwise fluction velocity u' exceeded 18 $\pm$ 2.5% of the free-stream velocity breakdown would ensue for all Re_x between 2×10^4 and 10^6. One notes that u' fluctuations exceeding 12% of maximum mean velocity in developed turbulent layers have not been observed (flat-plate boundary layer, pipe, channel flow). An r.m.s. fluctuation of 18% of U_e would represent a very intense disturbance indeed. Such intensities are unlikely to occur "naturally" and may be difficult to trigger artificially without recourse to sparks. Grid generated free-stream turbulence decays rapidly to levels below 6% and lower. Thus, according to Elder's criterion, even such large non linear disturbances would still have to be amplified upon entering the boundary layer or remain sterile. The nature of the processes generated by Elder's spark can only be surmised, but there seemed to be no sharp fluctuation maximum across the layer thickness. In contrast, Klebanoff et al (Ref. 38) found a sharp peak of u' of 16% of U_e at y/δ of 0.4 at the final

breakdown of the T-S amplification chain, in general agreement with the maximum values of Kovasznay et al, Ref. 37, Tani and Komoda, Ref. 44, and Tani et al, Ref. 125.

It would seem unwise to draw any public conclusions from such heterogeneous information at this time other than that (a) the turbulence triggering scales can be commensurate with critical 3D roughness size at low speeds and (b) even in presence of high free-stream fluctuations some amplification such as that of the near-wake disturbances appears necessary. Tentative conclusion (b) provides some reassurance that "finite-amplitude" disturbances, unless they distort the mean profile into some other powerful enough "amplifier", may not be as likely to trigger sustained turbulence as the ignorance-based cliche's seem to make them. However, in this connection a general comment of Coles, Ref. 162, should be quoted: "The main difficulty in the case of boundary-layer flow is that the inherent increase in Reynolds numbers with distance may act to convert a temporary, abnormal response to a strong disturbance into a permanent one." The tentative model of the boundary-layer responses surmised from the information of this and the preceding Subsection is schematized in Fig. 15. There is a distinct qualitative difference in the 2D and 3D developments for both the T-S route and the bypasses. Insofar as the roughness instability process differs from that of the T-S pattern and from its final breakdown, the 3D roughness of critical size charts yet another road to turbulence. The relative success and consistency of the newer correlations for the critical 3D roughness size at low speeds (e.g. Refs. 132-134) may well be due to the more direct chain of events and the apparent absence of pre-turbulent scale change.

To what extent can the preceding concepts be trusted when the major parameters like pressure gradient, free-stream turbulence, and cooling are varied? Most of the cited references and others like Refs. 135 and 136, agree that the critical Reynolds number for either 2D or 3D roughness elements is insensitive to the level of free-stream turbulence and to pressure gradients. Yet Klebanoff's spectra show clearly that the amplification feeds on the tunnel disturbances in the sense of (b) p. 23. And Fig. 7 of Smith and Clutter (Ref. 132) indicates changes in transition itself for a range of unit Re, apparently when the turbulence level drops below some level. The concepts of this and preceding Subsection allow for a variety of behavior especially when the relative roles of the linear and non linear phases of the phenomena tend to shift. General conclusions from macroscopic experiments in limited domains of the phase space of the parameters (such as dimensionless combinations of k, x_k, δ, U/ν, intensity and 3D spectral shape in the case at hand) should therefore be viewed as tentative probability statements and their range of verified applicability underscored. Systematic macroscopic experiments exploring the trends with wall cooling (through the single term ν above) would have a bearing on the early-transition paradox of blunt reentry bodies (Section II) and could clarify the scaling laws still further. In this connection there is much food for thought on the roughness role in the detailed report on cooled blunt bodies at low speeds by Dunlap and Kuethe (Ref. 140).

The blunt body paradox involves the effects of a favorable (falling) pressure gradient as well. The semi-microscopic experiments of Peterson and Horton (Ref. 141) in the highly favorable pressure gradient on a large sphere demonstrate conclusively that 3D roughness elements can generate turbulent wedges in the forward region where the boundary layer is unquestionably stable with respect to T-S waves. This circumstance provides further evidence that the amplification downstream of the roughness which culminates in the seeding of the turbulent wedge is alien to the T-S mechanisms. There is speculation that the large convective accelerations may feed energy into the streamwise vorticity disturbances which are generated by the obstacle. The cold facts are that the critical Reynolds numbers Re_k, $ku(k)/\nu$, of Peterson-Horton fit the various correlations based on flat-plate data well so that no influence can be inferred on the present evidence. On the other hand, evidence for the presence of the vortex-stretching mechanism in the accelerating boundary layers on two-dimensional cylinders subjected to artificial free-stream turbulence appears to be growing. For instance, Kestin and Wood's (Ref. 142) carbon-paper technique displays the formation of longitudinal vortices some distance downstream from the stagnation line when turbulence with u'/U of 0.02 impinges on the smooth cylinder - see also other references in Ref. 142. The preferred width of an individual vortex is on the order of a boundary layer thickness, a new scale in the complex of instabilities. Its possible influence on the criteria of turbulence seeding would probably depend on the strength of the spiral motion which may be quite small.

When it comes to the major parameter of Mach number no microscopic information exists concerning either 2D or 3D roughness behavior. One can speculate that the role of 2D roughness would follow the Klebanoff pattern (Ref. 94) and that the Mack-Brown programs could provide a guide if one fed in the separated mean profiles. One should keep in mind that the amplification trends with cooling are opposite for the attached layer and the "fully separated" mixing layer - see Gropengiesser, Ref. 70. Some of these effects were already discussed on p. 16, re Fig. 7, indicating decreased 2D tripper effectiveness as M rises.

As to 3D roughness at supersonic and hypersonic speeds one can only go to one's preferred source of corresponding correlations and use them on faith. They represent a great deal of effort and can be reconciled only by the authors themselves. With respect to the three major contenders (Refs. 102, 143, 144), a user, N. W. Sheetz in Ref. 83 states: "There is a great deal of uncertainty in the proper $Re_k|_k$ (critical roughness Reynolds number based on undisturbed conditions at top of roughness). Values from the three references vary from 400 to 10,000 at a local M of 3 and from 300 to 40,000 at a local M of 6." The latest updating of the Potter-Whitfield school can be found in Ref. 145 together with the claim: "The correlation of Potter and Whitfield provides the only method available, to the authors' knowledge, which offers a quantitative estimate of the transition location for a given roughness size." Strong support for the P-W method, which uses the <u>higher</u> $Re_k|_k$ values, came from a competing laboratory - see

conclusion 5 of Holloway and Morrisette, Ref. 268. However, after their latest experiments, Ref. 269, Morrisette et al point out that "artificial transition does not move to the roughness position at hypersonic speeds", and suggest the usage of the bend in the Re_{tr} vs Re_k curve (or equivalent) for correlation purposes instead of the position of the trip itself. Whatever progress is made, is for low Re/in and large roughness sizes - away from the conditions of transition reversal with temperature and of lower Re_{tr} values in ballistic ranges.

Reference 145 and other recent papers (e.g. Refs. 110, 146-149, 268, 269) call attention to the strong flow-field distortions which the roughness elements generate at supersonic and hypersonic speeds. They bring about regions of very large heat transfer associated with the horseshoe vortices (end of Section III-5) and with the increasingly strong shock waves. In industrial hypersonic wind-tunnel testing, roughness is often used to "get some measurements of turbulent heat transfer". The severe distortion of the flow field makes reliable conclusions rather difficult. In order to minimize such distortions Hama (Ref. 150) proposed a high-speed version of his earlier tripping device (Ref. 151). Why indeed should roughness be spherical or cylindrical? However, protuberances occur on practical vehicles as a matter of course, and especially so when the surface is ablating. Since lateral pressure gradients due to protuberances are likely to go up with M^2, one may expect formation of stronger longitudinal vortices with the concomitant danger of hot spots. (The thicker boundary layers may cushion the protuberance pressures but their low skin friction makes them more susceptible to cross-flow near the wall.) Furthermore, persistence of the rotational flow on the scale of the boundary layer thickness might make the breakdown to hypersonic turbulence, if it comes, more rapid than in the corresponding low-speed mechanism of Tani et al (end of Section III-5 and Ref. 125). Since next to nothing is known concerning the structure of hypersonic turbulent boundary layers and what makes them self-sustaining, the estimator of transition does not even have a clear intuitive target.

The distortion of the field and thickening of the boundary layer are probably responsible for occasional distinctly odd effects. One would expect 3D roughness at high Mach numbers to be either ineffective or to move transition upstream. However, it is hard to fault the discussion of Holloway and Sterrett (Ref. 152) concerning their Fig. 6f. It shows that a 3D element of height equal to two thirds of the local boundary layer thickness shifts the end of transition region some 17% downstream, while barely affecting the start of the transition region. Similar effect was observed by Softley (Ref. 109).

In fact, when a user of the information dips into the original data, he often finds himself a little confused and emerges with a healthier attitude with respect to the correlations. Some additional recent experiments are recommended in order to acquire more feeling for the associated probabilities: Bandettini and Isler (Ref. 153), Van Driest and McCauley (Ref. 154), McCauley (Ref. 154), McCauley et al (Ref. 155), Nagamatsu et al (Ref. 156), Dunevant and Stone (Ref. 157), Van Driest et al (Ref. 158) and Van Driest and Blumer (Ref. 159). Even from the data which filters into the final publications one senses much randomness in the data and some arbitrariness permeating the final conclusions.

There is the question of *detection techniques* and their relative indications which *also* vary with the major parameters. This important question fortunately is not germane to the objectives of the present monograph. Hence the reader is referred to Laufer and Marte (Ref. 57) Bradfield (Ref. 160), Potter and Whitfield (Ref. 102), Pate (Ref. 161) and to the latter's unpublished correlations for at least partial discussion. An associated question concerns the reasoning leading a particular experimenter to focus on the *beginning* or the *end* of the often extended *transition* region. Practically both provide important information. Theoretically, more rational understanding should be possible for the beginning of the transition region (assuming that there are no fixed turbulent wedges present as is often the case - see Fig. 3 of Ref. 33) because the chain of events is less complex and because the better-understood linear region then forms a more significant portion of the total length. Self-respecting experimenters and correlators should report both. Some of them do face the problem of having detected only some mean position, especially when small-sample visualization techniques are used. Thus Potter and Whitfield (Ref. 102) chose the center of the transition region since "any assumption regarding transition point is reasonable provided it is used consistently". Unfortunately, inconsistency abounds among the families of experimenters and correlators. The author would propose a *mandatory usage* of *two positions*, whenever known, not only because a great deal more important information is thus conveyed but also because the combination provides some feeling for the quality of the data.

7. TURBULENT SPOTS AND INDUCTION PROCESSES AT HIGH SPEEDS.

The tentative model of the roughness-induced processes of Fig. 15 culminates in a symbolic seed of wall turbulence. There is, of course, a period of gestation between the accelerated spectral evolution following the "spikes" or equivalent breakdown (Section III-1) and the developed state of Emmons' spots. In view of the probable non uniqueness of the breakdown, this early period is unlikely to possess general features characteristic of all transition in attached layers. However, the three-dimensional, non linear, stochastic processes within the low-speed spot itself apparently endow it with more generic significance even early in its development, see also Mitchner (Ref. 163), Schubauer and Klebanoff (Ref. 31), Meyer and Kline (Ref. 34), Elder (Ref. 139), and Coles (Ref. 164). This opinion is strengthened by Tani's report (Ref. 27) on his work with Komoda and Handa, using the penetrating tool of conditional sampling introduced by Kovasznay. The picture of Schubauer and Klebanoff (Ref. 31) is supplemented by a wealth of intriguing detail. However, a satisfactory idealized model which would capture the main mechanisms apparently remains a gleam in the future. When it comes, it is likely to combine the dualistic vorticity-pressure induction at distance, operating in part on the reservoir of organized mean vorticity near the wall, with the convective-straining features of the layered motion.

At high speeds, especially hypersonic ones, one would expect the features of induction at distance to be modified because the process can operate only within the Mach region of influence with respect to the moving "source". Communications of signals, essential to cooperative movements across the layer, should be hampered in some ways. Upstream influence remains possible through the subsonic sublayer but appears to extend less than a boundary layer thickness in supersonic turbulent boundary layers (Ref. 164, 61, 62). For transition of adiabatic hypersonic boundary layers the high level of fluctuations usually associated with approach to breakdown occurs near the theoretical critical layer at the outer edge. Since in general this layer is traveling with a subsonic velocity with respect to the free stream, upstream feedback[8] in this region remains possible through the free stream as well, weakened as it must be.

As far as it can be judged by the fluctuation measurements within the turbulent boundary layers, their structure is not palpably influenced up to Mach numbers of about 5 by this "communication problem"

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8. To what extent the level of amplification of the laminar layer is decreased at supersonic speeds by the diminishing feedback is difficult to judge because the instability theory hides such features through the assumption of disturbances of the form exp. $(\alpha x + \beta z - \alpha c t)$. Clearly this feedback increases with the obliquity of the waves probably contributing to their higher instability at supersonic speeds.

and by the increased radiation of sound associated with it (Ref. 53). This hardly gives one license to assume that the hypersonic features of spot formation and growth will pattern themselves after the low-speed Emmons-Schubauer-Klebanoff model. Flattened out, randomized, highly swept back eddies, still anchored to the wall would appear as the formations of turbulence most consistent with the inferences from low-speed information and with the hypersonic environment.

The preceding remarks should remain valid with respect to the close kin of the turbulent spots - the turbulent wedge. The basic phenomenon of lateral (or transverse) contamination appears to have enjoyed only one serious (microscopic) attention (Ref. 31) since its discovery by Charters in 1943, Ref. 166. As the turbulence within the tongue proceeds to seduce the neighboring demure laminar layer into its frenzied dance, it exerts a lateral and upstream influence. Is an amplifying process like those of Fig. 15 involved? Or is it a matter only of the scrambling of the organized vorticity reservoir and the nonlinear vorticity production, eq. (1), Section III-1? These basic questions cry out for attention of the practitioners of multiple hot-wire arrays and of conditional sampling. The evidence of mean mass transfer from chemically coated models indicates that the phenomenon persists to the highest attained speeds but with a reduced lateral reach. The decrease of the lateral spread was observed with a hot wire by the author already at the low Mach number of 1.77 (Ref. 113) and corroborated by Korkegi at M of 5.8 (Ref. 167). An intriguing largely unpublished collection of sublimation studies at moderate supersonic speeds behind single roughness trippers exists at NASA Ames Laboratories (Ref. 168).

The optical properties of the unsteady spots at supersonic speeds make them more readily observable (especially on bodies of revolution) than at low speeds. The variety of observed patterns of seeding and growth of Jedlicka et al (Ref. 114), James (Ref. 116), Spangenberg and Rowland (Ref. 169), Evvard et al (Ref. 58) and others should make one wary of generalizations that have been found in the literature. A few counter-quotations are perhaps in order. Spangenberg and Rowland's detailed study with a cylindrical lens camera at M of 1.96 states. "A turbulent front is maintained by the addition of turbulent spots of finite size at its trailing face. This front is not self-sustained, nor is it propagated in an upstream direction." "An increase in roughness and an increase in Reynolds number per unit length both cause an increase in spot production frequency;" "The trailing face of turbulent spots have streamwise velocities at the time of their eruption of something less than 1/2, perhaps even as little as 1/4 of free-stream velocity. They soon accelerate to a constant velocity of about 0.7 free-stream speed. The growth rate of spots perpendicular to the model surface is precipitous at the time of birth. Spots grow to about three laminar layer thicknesses while they travel a distance equal to their spacing."

The last three quoted sentences on the gestation behavior and growth do not quite fit the low-speed picture, especially in the matter of the trailing-edge speed. Since the critical layer at M of 1.96 is located at y/δ of 0.5 the growth of fluctuating motions in the perpendicular direction of hypersonic speeds where the critical layer is way out may also be different. Hot-wire and hot-film studies of Potter and Whitfield (Ref. 103 at M of 5), Nagamatsu et al (Ref. 156 at M of 10), Softley et al (Ref. 109 at M of 10) Staylor and Morrisette (Ref. 170 at M of 6) and Maddalon and Henderson (Ref. 171 at M of 7.4-17.6 in Helium) indicate that the breakdown propagates inward from the outer layer. Apparently in presence of the communication delay, there can be non negligible differences in indications of the beginning of transition by different probes (Ref. 171). References 103 and 170 actually mapped out in x and y the isolines of constant r.m.s. voltage response of a hot wire through the transition region showing that x may double between the position of the start of violent activity in the outer region and the position at which the high voltage response spreads to the wall region. Theory of the interpretation of the signals (Ref. 62, 63, 65) and Kendall's detailed experience at M of 4.5 (private communication) indicate that these recorded voltages may be distorted by the non variable settings and by marked changes of the wire sensitivity to velocity, density, and temperature fluctuations with wire overheat and local mean-flow properties, which change non-similarly through this region. Nevertheless, these studies point to the probability of an altered structure of the transition region at hypersonic speeds.

Returning from the timewise averages to the optical snapshots of the mop-up brigade of turbulence, the Spangenberg-Rowland view at M of 1.96 on a hollow cylinder is one of explosive births far from the leading edge. The hot-wire studies above support this view at Mach numbers of 5 and 6. On the other hand, the collections of shadowgraphs on cold models for $2.7 < M_{\infty} < 10$ in references 114 and 116 contains a substantial proportion of cases where the spots, judged by the tell-tale pressure wave imprints of the "explosions", originated at or very close to the leading edge or nose. Despite their concern with extreme smoothness, Jedlicka et al (Ref. 114) state: "Since seemingly identical models often produced decidedly different numbers of bursts it was evident that bursts were being caused by subtle factors" and "From these data, it appears that the bursts were produced by surface roughness especially near the tip, and by abrupt change in slope near the tip.... Greater susceptibility to bursts is indicated in the high Reynolds number tests." Also: "Disappointing results were produced in the case of the models for which the maximum polishing effort was expended."

Evvard et al (Ref. 58) aver that only 3% of their schlieren pictures on a 10° (total) cone in a M = 3.12 wind tunnel showed any bursts separated from the main body of turbulence. W. R. Witt, Jr. advised the author that he has not seen any bursts on cones with total angle over 40° during his years of experience at the Naval Ordnance

Ballistic Range. A. Seiff of NASA Ames Laboratories has observed both types of turbulent front distributions. By modifying the oncoming free-stream turbulence at M of 3.12 Evvard et al changed drastically the stochastic behavior of the turbulent fronts, etc.

Taking into account the larger numbers of parameters and instability modes at supersonic speeds (both of which affect the seeding) and the probability that each spot sweeps out an angle on the order of one half of that at low speeds, one should expect the source density function $g(x,z,t)$ of Emmons (Ref. 8) not to be as relatively simple as at low speeds. The computational approach of Emmons and Bryson (Ref. 172) would have to be considerably generalized by introducing a number of uncertain hypotheses and of adjustable (ignorance) parameters, e.g. Refs. 297, 299. It is hard to see how the final results would contribute to either the understanding of the phenomenon or to prediction techniques one could trust in design. By plotting the distributions of a number of wall variables through the transition regions of different experiments the author found that only about a half of those tried could be fitted to the low-speed probability distribution curves of Dhawan and Narasimha (Ref. 173). He particularly experienced difficulties in the variation of the transition Reynolds number spread Re (end) - Re (beg.), in relation to the beginning Re_{tr} for which he could find frequent behaviors vastly different from the suggested low-speed correlation of Ref. 173. In order to get some practical feel for such an approach the author recommends correlating the transition regions of Ref. 174 at the one Mach number of 4.95 and then adding cooling, changing Mach number etc. Insofar as the exercise helps one to sharpen one's sense for the trends with parameters which could relate to a physically sound model, it is perhaps worthwhile. However, before undertaking any prolonged labor one would do well to ask oneself two questions. Is the approach contributing to any basic understanding? Is it likely to lead to a result on the basis of which one would be willing to take responsibility for transition design on a N-million dollar project? Researchers at NASA Langley Laboratories decided that the last two questions were more likely to be answered in the affirmative if the prolonged labor were to be done by a tireless and objective computer. The results should be interesting.

8. THREE-DIMENSIONAL BOUNDARY LAYERS AND DIFFERENT BREAKDOWNS

In Section II the existence of T-S fluctuations with oblique wave fronts in a two-dimensional mean boundary layer was introduced as a necessary consequence of three-dimensionality of free-stream disturbances. It was seen there and in Section III-4 that at supersonic speeds these disturbances are generally much more amplified than their two-dimensional cousins, see Figs. 9, 10 and 12. In Section III-1 and III-5 previously unsuspected slight three-dimensional perturbations of the mean boundary layer were observed as major low-speed accelerators of transition by their meddling not in the T-S amplification process but in the subsequent regimes of non linear growth and breakdown, see Figs. 1 and 2. In that regime the streamwise component of vorticity, ω_x, emerged from infinitesimal obscurity and played a major role in the oncoming revolution, mathematically reflected in the production terms of Eq. (1), Section III-1.

When the mean boundary layer is three-dimensional in the first place, a number of new terms in Eq. (1) and in the associated convective derivative of vorticity appear in the linearized equation, corresponding to richer vorticity interaction and amplification in the early linear stages. Referring to Fig. 16, the velocity vector at a position x, z of the surface is seen to twist out of the plane defined by the normal direction y and by the outer streamline i.e. by the x direction. With the aid of the decomposition of the twisted vector family on the streamwise yx tangential plane and the yz crossflow plane, one can start visualizing the three-dimensional mean vorticity distribution which ultimately feeds the unstable vorticity disturbances.

Again, the disturbances are thought of as a superposition of Fourier components of all orientations at the given point x, z. However, as one proceeds to the neighboring points the local orientation of the wave front may change because of non uniformity of the crossflow. In other words, from a global look, the wave fronts of a given family of disturbances may be curved - e.g. spirals in the three-dimensional boundary layer on a rotating disk. One should examine the eigenvalue problem and local amplification rates in all these possible directions and find that direction in which the profile is first unstable and that in which it has maximum amplification at a higher Reynolds number. The wave disturbances with the front parallel to the z axis in Fig. 16 correspond to the normal 2D T-S waves with their viscosity-induced relatively low amplifications. The wave disturbances with a wave front along the x axis are primarily sensitive to the mean velocity cross-flow profile. Figure 16 shows that this profile has a point of inflection indicating the

possibility[9] of a more rapid inviscid amplification along that direction (see Section III-2).

J. T. Stuart (Ref. 175) saw that the presence of these inflection points made possible a meaningful simplification of the equations, namely the inviscid approximation. He singled out the plane rotated yet another 30° past the cross-flow plane in which the point of inflection of the mean profile coincides with the y axis in Fig. 16, i.e. has zero velocity with respect to the wall at a height y_I. Roughly, amplification of that family of waves corresponds to an increasing concentration of vorticity oriented perpendicularly to that special plane at a height y_I. Because of the vanishing relative velocity, this vorticity concentration would form a stationary wave and could be made visible by sublimation or smoke techniques. Gregory indeed documented visually the existence of the aforementioned spirals on a rotating disk (Ref. 175, also citation in Footnote 8) in rough agreement with Stuart's approximations.

Prof. F. N. M. Brown's Fig. 17 demonstrates the equivalent vorticity formations on a spinning projectile. Gregory and Walker can identify spiral vortices on a rotating disk for a range of applied suction, Ref. 176. Developed stationary vorticity waves exist (Fig. lX.20 of Ref. 175) on most sweptback surfaces past their own special critical Reynolds number. They can be sensed by smoke and sublimation techniques and by spanwise traverses of pitot tubes, hot-wires, or hot-film gages, both at subsonic and supersonic speeds, e.g. Refs. 177 to 180. They are visible in shadowgraphs as they leave the trailing edge of small delta wings propelled in the ballistic range, e.g. Fig. 6a of Chapman, Ref. 181.

There is little doubt that presence of mean streamwise vorticity component destabilizes the layer with respect to this still different competitor in the instability race. The normal T-S amplification also proceeds at its rate, but this dynamic (inviscid) instability develops past the exponential stage to the non linear stage first. It would be interesting to have measurements on the non linear inhibition (see Section III-1), if any, of the competing T-S mode. The dynamic vortical motion itself apparently grows at most linearly after it reaches the non linear stage. Yet it leads to earlier-than-normal

9. The presence of the inflection point does not necessarily make the profiles unstable. A succinct and lucid summary can be found on pp. 800-803 of Shen (Ref. 86). J. T. Stuart who contributed heavily to the formulation of the theory reviews it and associated low-speed experimental results on pp. 550-558 of Ref. 85. The frontispiece of Ref. 85 and Fig. lX.20 opposite p. 550 are recommended viewing.

transition both at subsonic and supersonic speeds. Figure 17 may contain a clue (not a proof) to a reason for the early onset of self-sustaining wall turbulence in such cases. Scattered measurements and W. B. Brown's computations of the wave number characteristics for the case of the rotating disk, Ref. 182, indicate that the lateral scale of the longitudinal vortices which are most likely to be amplified, is on the order of one to three boundary layer thicknesses. The breakdown pattern of Fig. 17 differs both qualitatively and quantitatively from that of Fig. 2. In particular it seems to take place without a change of scale which occurs for the T-S breakdown. It would appear that the intrinsic scales of this new class of 3D disturbances is commensurate with the scales of the vortical motions of self-regenerating turbulence. An intensity criterion is missing, but the apparent affinity of scales of the pre- and post-breakdown motions may be the feature responsible for the early transition. The reader will recognize that a similar affinity may be responsible for the non T-S breakdown of the three-dimensional motions generated by a postcritical 3D roughness element, Fig. 15.

The condition of affinity of scales as part of the breakdown criteria appears to have quite general validity (see also Sections III-1 and III-2). In the meterologically important three-dimensional boundary layers in rotating systems, the Ekman layers, the diversity of possible motions increases. According to Faller and Kaylor, Ref. 183, and Tatro and Mollo-Christensen, Ref. 270, two spiral-like instabilities occur independently or simultaneously. The long-wave instability (Type II of Ref. 183) appears to require an additional reorganization of scale and orientation ("gill instability") before it undergoes final breakdown to turbulence. The breakdown of the F-K instability of Type I is qualitatively different and often appears to take place as a non linear interaction between Type I and Type II vorticity formations which cross at an angle. One or the other type of breakdown to turbulence may occur depending on the level (and presumably spectra) of "natural" disturbances present in the system (Ref. 183). If one were to formulate this problem in a suitable phase space of parameters, there would be a change in location of transition with disturbance intensity as the parameter responsible for the switch. If one did not know of the existence of both modes, one could hardly trust any "blind" correlations based on the same parameter.

Considerations of this type suggest that a more systematic approach, coupling theoretical and experimental research in transition of typical three-dimensional boundary layers at high speeds, may be in order. In connection with aircraft design A. Seiff wrote in 1958 (Ref. 184), "The principal deterrent to fully laminar flow is the adverse effect of sweepback of the wing leading edge". At hypersonic speeds the presence of ablation may make the design even more sensitive to cross-flow. Not much understanding has been achieved at high speeds since Seiff's summary. However, considerable clarification took place at low speeds thanks to British research, e.g. Refs. 185-187 and to the work of the NorAir group associated with W. Pfenninger in conjunction

with NASA Ames Research Laboratories and AF Flight Dynamics Laboratory at Wright-Patterson Air Force Base, e.g. Refs. 179, 188-194.

One of the more accessible sources of rather detailed information on the 3D stability behavior is NASA TN D-338, by Boltz, Kenyon, and Allen, Ref. 179, which is highly recommended in order to get a "feel" for the phenomenon. Pfenninger and Reed's very readable, perils-of-Pauline type, account of the transition design problems contains a number of lessons applicable to the hypersonic effort as do the three companion papers, Refs. 189-191. In particular, the presence of a number of competitive modes of instability and transition was identified and designed for through a series of experimental and theoretical steps. Since the streamwise vorticity instability does not produce turbulence immediately, an empirical delay factor based on the cross-flow parameter of Owen and Randall (Ref. 195) was refined and carefully checked out under controlled conditions. The environmental hazards were recognized and the empirical factor revised to allow for the effect of heavy acoustical disturbances which may be present on some jet aircraft near sonic speeds. The theoretical instability program of Brown (Ref. 182) helped in design and optimization of the Laminar Flow Control system. While a LFC system is unlikely at hypersonic speeds the NorAir experience with suction and roughness problems illustrates the following general lesson. Once one mode of instability is strongly stabilized, other competitive phenomena, hidden hitherto under the noise level, can come out and plague a design - the principle of dominant and multiple responsibility.

One example of Coles' warning concerning the temporary abnormal response to a strong disturbance becoming permanent, p. 32, plagued the design of both the X-21 airplane (Refs. 192-193) and the Handley Page laminar flow suction wing (Refs. 185-187). The finite disturbance of a developed turbulent boundary layer on the fuselage tended to contaminate the swept-back leading edge of the proposed laminar wing - permanently. In the presence of the sustained supply of vigorous turbulent disturbances from the fuselage, the spanwise flow along attachment ("stagnation") line apparently could not assume its normal reasonably stable state.[10] Finally, by various patented diversion schemes (Ref. 196) the turbulence was kept away from the attachment line and the wing remained laminar to considerably higher Reynolds numbers. The solution called for a better understanding of the critical conditions for finite and infinitesimal instability.

There seems to be little excuse for not extending Brown's instability program (Ref. 182) to hypersonic speeds. Reshotko has prepared the theoretical background in Ref. 197 some time ago. Based on Mack's supersonic experience and Stuart's cross-flow experience, there is a high probability that already the inviscid formulation will provide most significant guidelines for understanding and sorting out of the complicated phenomena. Remembering the sensitivity of Mack's calculations to the mean boundary layer profiles, good computing methods for the three-dimensional inviscid streamline and pressure fields (say as function of angle of attack) and for the mean 3D boundary layer development are important prerequisites for either predicting (correlating) or

10. Boundary layers on sidewalls of hypersonic tunnels may be similarly contaminated by turbulence from the low-supersonic nozzle sections; see p. 62.

for computing via instability theory. One may digress to remark that an early overall 3D approach to flow computations directed at both T-S led and cross-flow led instabilities by Eichelbrenner and Michel (Ref. 198) appeared quite successful for the simpler low-speed conditions. At hypersonic speeds, the information must include the laminar heat transfer distribution, with ablation (if present), as it would exist in absence of transition. The study of, for example, Cleary's experimental results on a simple blunted cone at an angle of attack (Ref. 199) acquaints one with some of the field peculiarities, including peculiar formations that are apparently not quite transition (Fig. 24 of Ref. 199): "Preceding the turbulent flow is a region of transitional or incipient turbulent flow that is characterized by what appear to be vortex filaments with their axis somewhat alined with the flow". Is this associated with the instability of the 3D boundary layer or is it related to the complicated entropy layer flow as well?

References 200-208 each contain nuggets of observation and wisdom at times rubbing one's preconceived views the wrong way. The interrelated effects of leading-edge bluntness of leading-edge nonuniformity, of sweep, and of unit Reynolds number perhaps deserve singling out. In Ref. 200, Ginoux, the leading student of supersonic longitudinal vortices, expresses doubt that the visible striations on supersonic surfaces with swept leading edges are necessarily due to the crossflow instability. In his own careful experiments he suspects the nonuniformity of the thin leading edge as the cause. As was commented in Sections III-5 and III-6, the ensuing $p(z)$ can and often does induce local cross-flows downstream. At low speeds approximate theories (Refs. 209, 210) indicate that the effects on the mean boundary layer persist and grow linearly with the distance from the leading edge (see also experimental evidence of Bradshaw, Ref. 211). The more singular character of the leading edge at supersonic speeds could be expected to produce similar if not stronger effects. In principle, an infinitely sharp wedge-airfoil with supersonic leading edge and without leading-edge viscous interaction effects should not be sensitive to the sweep angle, there being no lateral pressure gradients and hence no cross-flow. Waviness of such a sharp edge would produce Ginoux's effect.

When one increases the leading radius, uniformly, one introduces strong $p(z)$ over the curved portion and feeds in, so-to-speak, a Dirac-like cross-flow input. Simultaneously one produces an entropy blanket which makes the boundary layer non similar in x as per Section III-5. The two effects compete, one presumably destabilizing the layer and the second tending to postpone transition. References 161, 180, 191 and others indicate that the destabilizing effect becomes dominant with increasing sweep, as seems reasonable. If one gets increasing indication of longitudinal vortices when rotating the same wedge in the same tunnel, the increasing part of the effect can hardly be ascribed to leading-edge nonuniformity. And if one changes the unit Reynolds number as well, what should the effect be? According to References 81, 180, and 191, the transition Reynolds number becomes

less and less sensitive to the unit Re parameter. The environment of the tunnel has not changed, but the actual length of the laminar layer to transition has decreased. Again it seems that contrasts of this type hold clues to the basic mechanism behind the ignorance unit Re parameter.

5. FREE FLIGHT INFORMATION AND TEMPERATURE SENSITIVITY.

After the application of the asymptotic instability theory by Lees (Ref. 55) indicated the possibility of complete laminar stabilization by cooling at supersonic speeds (see comments on Fig. 7) NACA launched a long-range flight test program to study its implications, Refs. 212-225. Study of such reports can become quite frustrating because one is never sure of the condition of the model, especially roughness and local damage (and angle of attack for sharp bodies). There is no way of looking "microscopically" nor of rechecking a reading that looks suspect. A quotation from Ref. 223 (p. 8) provides an illustration: ..."shortly after 8 seconds the data became erratic. It was conjectured that deformation of the nose ... considered unreliable." Wind-tunnel researchers could find fault with the conclusions from the data that was kept, being used to an experimental discipline where better control and rechecks are not only possible but mandatory. (See Section III-4 for contrast.) For flight data, the "overall inference in context" probably justifies such judgements, as of high probability. The long-range aspect of the NACA program and the cumulative experience undoubtedly contributed to the quality of the flight test observations. By contrast industrial flight tests are often hampered by short-range objectives, overtight budgets and schedules, and the lack of control over important operations. The contract pressures tend to breed reports in which it is difficult to separate factual observations from interpretation based on current preconceived ideas.

Each free flight cuts a different trajectory through the poorly mapped phase space of major parameters. One must therefore expect surprises as the parameters vary simultaneously and may switch from regions of one dominance to another, the cross-over conditions being probably dependent upon other, possibly dormant parameters such as roughness. Before examining in more detail two such intriguing cases from Refs. 214 and 220, it is desirable to let the free-flight researchers speak on the question of roughness and the early-transition paradox of blunt bodies.

The transition Reynolds numbers, based on inferred momentum thickness θ, on blunt bodies of Refs. 221, 222 and 223 are reported to be in the respective ranges of 350-1600, 900-1200, and 800-2200 as compared with the range of 100-200 of Murphy and Rubesin, Ref. 17. The wind-tunnel experience of Dunlap and Kuethe (Ref. 140) and of their references points to roughness as a major suspect. In fact the implication of Refs. 221, 222, 223, 17, and 140 is that one has to reduce roughness below 5 microinches r.m.s. to avoid $Re_{\theta tr}$ on the order of 150-250 (the pessimistically - or realistically - accepted blunt limit) at free-stream unit Re_∞ on the order of 10^8/inch in flights with substantial cooling. Generally, there is no evidence of any beneficial effect of cooling on transition on the curved blunt surfaces. The trends with wall temperature appear to be monotonic.

The aforementioned experimental "spoiler" technique, p. 28, could be used to advantage in flight tests of roughness effects if packaging constraints are not prohibitive. For instance, a single test, with the mirror-like finish marred on purpose to a 25 microinch rms level over one half of the model (from an azimuth angle of 7° or so), would provide a controlled contrast test for the allowable-roughness inference of p. 46 with a much higher probability. The free-stream and vibration conditions would be alike - in contrast to repeated flights. This approach also appears desirable for "practical" flight testing where probable types of roughness of sizes befitting the design surface material should provide a "reasonable" lower bound. Flights along these lines have been reported in the range of local Mach numbers from 2 to 3.2 in Ref. 228. Experiences on the X-15 airplane are recounted by Braslow in Ref. 229, in particular: "Turbulent flow existed on the entire fuselage at all times during the flight as a result of a forward facing step between the high-speed flow-direction sensor and the fuselage." One wonders how such probabilities can be taken into consideration in early design.

When experiments at high unit Reynolds numbers are contemplated, in order to bring Re_{tr} within reach of small models, special care with respect to reducing roughness and measuring it is mandatory. To believe that the roughness is small is hardly sufficient. To measure it to the accuracy apparently required entails more sensitive techniques than the current stylus profilometers. At least that is the implication of the following selected experiences. The surface finish on the cited blunt bodies were quoted as: "average 6-8 microinches r.m.s. with maximum of 15 microinches" presumably measured with a stylus, in Ref. 221; "superpolished to 1-5 microinches as measured by interference microscope" in Ref. 222, and "2-3 microinches on hemisphere as measured with an interferometer" (Ref. 223). Though nothing has been said, there probably was protection against insects and dust in the lower atmosphere - see Ref. 226. The conditions for cone flights, yet to be discussed were described in Ref. 200. "The exterior surface of the entire nose was highly polished and the surface roughness, as measured by a Physicist Research Co., Profilometer (stylus, 1956 model) was from 6 to 10 microinches". Merlet and Rumsey write in Ref. 214: ..."Subsequent to the flight sample roughness measurements made with the Phys. Res. Co. Profilometer were checked optically with a fringetype interference microscope. The average roughness measured optically was 8 to 10 times (!) the r.m.s value read by the Profilometer for a copper sample." Apparently one should not thread the needle with boxing gloves on. The implications of the size of the stylus and of the force exerted by it are shown dramatically in Fig. 18 borrowed from Wilkins and Darsow, Ref. 227. These authors tackled the problem in depth unmatched elsewhere when it comes to transition measurements. They bring out the disqualifying characteristics of stylus devices and make recommendations illustrated in Fig. 18 based on their experience in high unit-Re environments of Ames Laboratories. Apparently, it is not enough to measure the roughness of a sample, but a few occlusions of the metal near the nose can have far reaching consequences. Sharp noses are especially sensitive to manufacturing and handling blemishes.

There have been no detractors of the wisdom of Wilkins and Darsow, but very few followers. The consequences make the high unit-Re research very demanding and costly. Fortunately, many research objectives do not call for the full W-D treatment. However, programs which aim at answering basic questions, such as the apparent contradiction between References 2 and 3, are unlikely to satisfy the community of scientific transitionists without it.

Turning to cone flights, one observes that the slope of the Reynolds number of transition with Mach number is positive for $1.5 < M\ 3.5$, apparently in direct contradiction to the wind-tunnel information. Furthermore, flight Re_x of the beginning of transition on cones can attain values of 90×10^6 at M_e of 2.7 (Sternberg, Ref.16), 30×10^6 at M_e of 2.9 (Rumsey and Lee, Ref. 220) and 33×10^6 at M_e of 3.15 (Merlet and Rumsey, Ref. 124) as compared to the adiabatic cone values on the order of 2.5×10^6 at M_e of 3 in wind tunnels. Actually, because of disparity in wall cooling and unit Re these points from different regions of the phase space cannot be compared and the differences cannot be rigorously ascribed to environmental disturbances such as the rising sound in wind tunnels. This is unfortunate, because this Mach number range also features the rapid stabilization of the 2D T-S instability mode and the emergence of the corresponding oblique waves, Fig. 10. In the quest for a more rational guide to transition estimates in this operational range of aircraft and missiles it would be desirable to resolve the flight-tunnel-range dilemma. The addition of the hot-and-cold running subrange to the NOL ballistic range (Ref.271), and further control of the model temperature, now allow firings in the low supersonic regime for which the wall-to-recovery temperature ratio can be varied between the normal tunnel and flight values. A series of firings roughly paralleling the conditions of the Van Driest-Boison experiments (Ref. 59), see Fig. 7, would therefore be highly welcome. One can see from the trends in Fig. 7 that the experimental observations are not necessarily irreconcilable. However, the proposed experiment would help to clarify the role of the environmental disturbances which have remained a matter of conjecture for twelve years.

The results from various cone flights could hardly be certified as consistent among themselves and small differences in roughness were singled out as the most probable causes, e.g. between Refs. 215 and 220 for which the nominal dimensions (but not the trajectory) were identical. However, intriguing rapid changes in transition location occurred on the two cited flights which reached the high values of 30 and 33 millions (Refs. 220 and 214). From study of Ref. 220 (15^o total angle cone) it is difficult to find a logical explanation for the sharp drop of Re_{tr} in 0.5 seconds from over 30 million to below 17 million while M_e increased from 3 to 3.5 and T_w/T_e remained unchanged at 1.15. Those who prefer roughness as their private bête noire, would probably focus on the following facts: The unit Re was rising rapidly and the now preferred temperature ratio T_w/T_r shifted from 0.46 to 0.36 during these changes. However, the drop on the 10^o total angle, long cone of Ref. 214

was from 33 to 23 millions in 0.5 seconds with Me changing from 3.15 to 3.0, T_w/T_e from 1.65 to 1.6 and T_w/T_r from 0.60 to 0.615. The cone had passed the peak unit Re 1.25 seconds earlier and was rising from 10000 to 12000 ft. in altitude. Based on free-stream conditions the Re/ft changes were from 12.2 to 15.0 millions for the 15° cone and from 17 to 15 millions for the 10° cone. The reader can exercise his ingenuity in rationalizing these results and in the process may acquire some appreciation for the difficulties of transition flight testing even on such simple bodies and in absence of ablation. For good measure, one can add that for the one second before the transition motion just described, the 10° cone of Ref. 214 had Re_{tr} increasing (contrary to stability theory) from 22.5 to 33 millions while the wall was warming up, T_w/T_r shifting from 0.38 to 0.60. This part of the development may correspond to the so-called transition reversal with cooling mentioned in connection with Fig. 7. The statement could be made somewhat stronger on the basis of a number of such occurrences in flight but the lack of control checks and of knowledge of detailed conditions counsels caution.

From the preceding sample experiences, one would be inclined to have recourse to flight tests as to a court of last resort, so to speak, when other research has prepared the ground for adequate interpretation. In many situations the anticipated operational conditions just cannot be matched in ground facilities and flight tests are imperative. Preferably they should be designed to aim at answering carefully prepared key conceptual questions (e.g. by using the "spoiler technique", pp. 28 and 47).

By contrast the ballistic range is a much tamer species of free flight - the relative control of the experiments makes it a scientific tool when manipulated by aerodynamically oriented experts. Nevertheless the previously documented large sensitivity to small variations in the nose region of the models and to poorly definable and controllable roughness presents considerable operational and interpretational difficulties. In connection with inadvertent blemishes an interesting successful application of the "spoiler technique" was recently made by Wilkins and Tauber to ablating plastic models fired in the Ames Ballistic Range (Ref. 230). On-purpose dimples did not necessarily heal by local ablation but generally were enhanced and led to longitudinal (presumably vortical) grooves and turbulent wedges. These artificial formations matched quite well patterns that had developed spontaneously on previous models certified as smooth. The probability of having thus found an explanation for the peculiar phenomenon in presence of ablation is therefore high.

At higher dynamic pressures the aerodynamically singular noses of metallic models can also start melting, e.g. Sheetz, Ref. 83. Before they melt, they are subjected to a mild thermal shock. Some observers believe that there can also be dangerous dynamic stress concentrations at the tip associated with the impulsive launching and subsequent vibrations. However, no quantitative evidence to that effect has been published. On the other hand, different materials have been used with

the same shapes and with consistent (though not rigorously controlled) results. In view of the achievable lack of aerodynamic disturbances in the "free-stream" in ballistic ranges, rationalizations of puzzling results center on these types of auto-disturbances and the possible presence of dust.

As the Mach number increases, the range pressures have to be sufficiently high to achieve the Reynolds numbers at which transition occurs on the tiny models. A compromise is called for and spherical noses of increasing radius are used, leading to the complications of combined entropy -layer, pressure-gradient, Mach-number and unit-Re effects. In Ref. 231, Sheetz presents a painstaking analysis of a large family of such cone firings covering local Mach numbers M_e from 2.9 to 9.1. The corresponding Reynolds numbers of transition, based on local momentum thickness (computed with ideal gas relations and the initial wall temperature T_w) as functions of the ratio of the initial wall temperature to the ideal-gas recovery temperature, T_w/T_r, are reproduced in Fig. 19. Of necessity a number of assumptions enter into the processing of the data involving flow fields not known in detail, and a large number of parameters. Figure 19 (and Ref. 231) represents a consistent interpretation - not necessarily unique[11] - of the mass of evidence. One does not need to take sides on the currently controversial apportionment of M and Re/L effects (see Introduction) to find the Mach number and T_w/T_r trends in Fig. 19 sufficiently convincing. In particular, the evident "transition reversal" with cooling at hypersonic Mach numbers cannot be dismissed.

Reshotko's progress (Ref. 79) in providing one consistent set of interpretations, based on linear stability theory of Mack, which could reconcile the Jekyll-and-Hyde reversal effects in different facilities in terms of the disturbances therein was mentioned in Section III-3. Reshotko goes through a series of estimates and judgements which "suggest that it may be possible to estimate the prospective involvement of higher modes in any given situation (i.e. experimental environment). The higher the value of U^2/ν (therefore lower $(\beta\nu/U^2)$-the less the importance of the higher (Mack) modes. It seems that it may be difficult to escape the higher modes in steady-flow hypersonic wind tunnels. On the other hand, they may have little relevance to transition on the ballistic range."

One feature not taken into account in Reshotko's model is the nose roughness factor which may yet offer a parallel or alternate reconciliation path. Both sets of effects can be present, of course, making a clean recognition more difficult. At the higher Mach numbers the cooling reversal is generally observed only at high unit Reynolds numbers. This fact, combined with the occurrence of the high density layer near the extremely cool wall, suggests that the effect of the roughness cannot be dismissed as a suspect. See also the idealized model of Potter and Whitfield, Ref. 232. Luxton, Ref. 233, presents a non quantitative model for the effect of very small roughness. The model needs much refining before it can be relied upon for explanation

11. See Section IV-4.

of even the trends. On-purpose roughness, combined with progressive cooling can cause transition reversal, e.g. Fig. 7, but the question is how small can it be and still be effective? The generally accepted conclusions concerning the roughness on cooled blunt bodies, described at the beginning of this subsection, and the experiences on which they are based shake one's confidence in one's ability of judging rationally what is "small enough".

One notes in passing Sheetz' rereversal at the one M_e of 5 in Fig. 19. Rereversals have been observed in the hot, high-R_e/L hypersonic gun tunnel by Richards and Stollery, Ref. 84, Richards, Ref. 234, and tendencies towards such behavior are reported sporadically. Insufficient number of observations have yet accumulated to warrant a public attempt at explanation. Obviously, the rereversal is unlikely to be caused by a roughness effect. In terms of the conveniently flexible phase-space concept, one looks for a separate parameter to take over the dominant role. It is of interest that reversals and rereversals appear to be R_e/L sensitive. In this connection it is worthwhile to note from Fig. 12, that Mack's theoretical instability quenching is R_e dependent. It would be highly desirable to have as complete a Mach number and Reynolds number map of the theoretical quenching trends as patience and finances can allow (see footnote 6, p. 16).

The highest Mach number at which a cooling effect of practical significance has been reported thus far in a wind tunnel on a simple model is apparently 6. Paying special attention to frost formation (a possible hidden parameter) Cary (Ref. 235) observed a typical monotonic increase in Re_{tr} (beginning) on a flat plate from 2.5 to 3.3 millions as the wall cooled from T_w/T_r of 0.75 to 0.2 at Re/cm of 0.27×10^6. The rate is relatively low but there was no reversal. Transition was sensitive to cooling of a cone-cylinder model of Zakkay and Callahan (Ref. 236) moving along the M_e 6.8 cylindrical portion after the strong M_e 4.24 conical prehistory. Wind-tunnel experiments of Deem et al (Ref. 237, flat plate, M_e of 10), Sanator et al (Ref. 82, cone, 10° total angle, M_e of 8.8) and Everhart and Hamilton (Ref. 238; cone, 7.5° total angle, Me of 9) appear insensitive to model cooling. Superficially there appear to be discrepancies with the trends of Fig. 19 which may or may not be reconciled as previously discussed. Since the reconciliation will probably involve either the disturbances in the environment or the quality of the surface, a designer may have to assess his probable conditions before making a decision on which wall temperature dependence he should use in his calculations.

At lower supersonic Mach numbers, there is ample evidence of transition sensitivity to wall cooling, e.g. Ref. 239-244. The interesting implications of Wisniewski and Jack's wind tunnel experiments (Ref. 243) are touched upon in Ref. 46. At these Mach numbers the questions center on the reversal phenomena and their possible causes. The possibility that a reversal might be inherent in the higher computational complexity of supersonic stability equations was

advanced by Reshotko, Ref. 245. His computations were based on an improvement of the Dunn-Lin (Ref. 25) asymptotic ordering procedure (Ref. 246 and 247) and displayed a non monotonic character which could lead to a reversal. It is generally agreed that the Mack-Brown equations (Section III-4) are more accurate than those used by Reshotko. Mack has not found any evidence of the non monotonic behavior of Reshotko's in his computer calculations of cooling effects, most of which, however, were for M of 5.8 and [illegible]

In connection with experiments on cooling effects on a flat plate at M of 1.8, K. H. Doetsch (Ref. 248) of Imperial College used Mack's "complete stability equations program" to map out neutral 2D stability curves at increasing cooling ratios. In view of the open question, he searched for solutions for cooling ratios far in excess of that for complete quenching of the 2D mode - without success. His family of neutral curves form an orderly set without any hints of the Reshotko effect. In particular, there was apparently no triple crossing of the complete stability curves as would be indicated in Reshotko's Fig. 2, Ref. 245 at M of 1.8 - see footnote 6, p. 16.

It is perhaps in order to reiterate that the stability theory indicates dependence not only on T_w/T_r (or on another suitable dimensionless ratio) but also on the level of the absolute temperature. This effect reflects primarily the strong influence the mean profiles have on the stability. The mean profiles themselves depend on the level of T through the non similar variation of the viscosity and heat conductivity with T. According to Mack (Ref. 1, Fig. 15.12) the lower ambient temperatures in wind tunnels make the first T-S mode substantially more unstable than free-flight conditions at the same T_w/T_r ratio for the computed Mach numbers of 3.5, 6.0 and 8.0. Should the generally more unstable first oblique modes and the second 2D mode (e.g. Figs. 10 and 12) be also taken into account at a point x as M, Re and T_w/T_r vary. The theoretical maximum integrated amplification based on measured tunnel and flight values of T_w and T_{stag} could well display peculiar behavior perhaps as baffling as the transition experiments.

IV. OPEN HIGH-SPEED QUESTIONS 1968

1. OPERATIONAL FRAMEWORK.

Section III examined, with an attempt at objectivity, the available information on the basics of boundary-layer transition and its relation to instability theories and other idealized models. In order to be more constructive, Section IV will present more personal comprehensive views of some high-speed transition researchers and of the author on the available tools, both experimental and conceptual These all may be changed by 1970 but in the meantime they will have hopefully provided a target for constructive discussion.

Starting with the conceptual tools, the author currently believes that the processes portrayed in Figs. 15 and 20, further augmented by possible, purely non linear bypasses of the T-S system are consistent with the bulk of the information in Section III. Fluctuation levels needed to trigger self-regenerative turbulence are probably high enough to require manyfold amplification of the disturbance input. Disturbances which do not modify the mean velocity profile are likely to be sufficiently small to need extended amplification according one of the number of possible linear modes. (Nonlinear terms at small disturbance levels can be safely neglected at first.) If all the active modes were relatively slowly amplifying like those in Fig. 10 then a substantial portion of the development of the final turbulence would be governed by the instability theory. For a given M and Re one could then generate not a perfect but a reliable enough rational guide to the role of the multiple parameters labeled "Operation Modifiers" in Fig. 20. Considering the effort that Mack and Brown have expended to map out a rather small subset of the conditions of interest, the desirability of a more urgent undertaking (first aimed at the modifiers $p(x)$, $p(z)$ and $\dot{m}$) would have to be generally recognized and implemented. This does not involve risks of uncharted theories but rather direct exploitation of the lessons of Mack and Brown.

Whether such a course is really desirable and useful depends in part upon the probability of occurrence of other more violent processes, called bypasses for short. This is not a matter of theory but of good experiment and cumulative experience. One needs some assessment of the probabilities and risks of a given design. Sternberg's V-2 (Ref. 16) may have reached an $Re_{x_{tr}}$ of 90 millions at one point but what low values were simultaneously present? The "spoiler technique of reasonable disturbances and roughness" in ground-facilities testing and in flight (Section III-9) may help to establish a safe lower bound once a prototype has been chosen. But an entirely different climate for design would be possible if one understood the main mechanisms behind the lower transition values. Once the mechanism causing the early transition near the leading edge of the swept Handley Page Suction Wing and of the X-21 was identified (Section III-8) a sensible course of action could follow. Incidentally, this case illustrates a nonlinear bypass that could be avoided.

An example of a bypass that remains not understood is the early transition on cooled blunt bodies. The combined impact of careful flight and wind-tunnel experiments (beginning of Section III-9) makes one pessimistic about the possibilities of avoiding this bypass at higher local unit Reynolds numbers, but the mechanism is still missing. The list of suspects includes 3D roughness maliciously cooperating with large negative density gradients in y due to cooling and vortex stretching due to pressure gradient in x to breed turbulent spots and wedges. The current best-bet mechanism appears to be an efficient variant of the upper path in Fig. 15. Conceivably, with the aid of clever ultramicroscopic techniques, the mechanism can be diagnosed and disected, but a cure is another matter. Without a cure, one has little choice but to accept the empirical lower bounds built on cumulative experience.

In the uncharted areas of new combinations of parameters, e.g. Refs. 276-278 similar killer bypasses may be lurking. They must be identified before safe and efficient design can proceed. It was stated above that such identification of bypasses is a matter of experiment. One could ask: How does one recognize a bypass if one does not know what the normal road looks like, say when the surface is ablating? This brings one back to the desirability of charting more territory among the Operation Modifiers in Fig. 20 with the Mack-Brown type of approach. It is the combination of linear theory and microscopic experimentation that can provide the framework of understanding. Without such a framework the good engineering intuition cannot get very far.

2. SOUND IN SUPERSONIC WIND TUNNELS AND CONSEQUENCES.

There is little question that the turbulent sidewalls of supersonic wind tunnels roar at the innocent laminar layer of a model intruding into its confines. At a Mach number of 1.77 the author was inferring noise levels on the order of 125 to 131 decibels, i.e. rms pressure fluctuations from 0.2 to 0.4% of free-stream pressure from his hot-wire measurements in 1954 (Ref. 113, 60) when he saw the Brinich Mach 3.12 movie (Ref. 97) from which Fig. 21 was excised. The recommended viewing experience is more than titilating. This (apparently first) usage of cylindrical enlargement of the boundary layer shows a great deal of unsteady activity that can be partly calibrated in strength and orientation against the visible weak leading edge shock caused by the small but finite leading edge thickness. The incoming wave disturbances are strong (perhaps with an unexpected degree of inferable two-dimensionality). Kendall's hitherto unpublished comparison, Fig. 22, of spectral voltage response of a hot wire as the sidewalls change from laminar to turbulent state at Mach 4.5 in the superclean J.P.L. supersonic wind tunnel should remove any doubts as to the power of the irradiation. A direct quote from Kendall's letter documents the effect of this change on transition: "At $M = 4.5$ stability-test plate had an x-Reynolds number of 3.3×10^6 (the flow remaining laminar, i.e. $Re_{tr} > 3.3 \times 10^6$). This is to be compared to Coles' values of 0.9 and 1.6×10^6 for the start and end of transition on a plate in the same tunnel, and same Mach number, but at high unit Reynolds numbers", i.e. undoubtedly with turbulent sidewalls (see Ref. 249). Kendall's measurements of the response <u>within</u> the laminar plate boundary layer to the turbulent sound of Fig. 22 have come to an end with the closure of the wind tunnel.

The only quantitative information on the radiation pressures comes from Laufer's painstaking measurements in the same tunnel, Refs. 66, 124, and 250. In particular, the ratio of the r.m.s. free-stream pressure fluctuation p' to the dynamic pressure (or to pM^2) was approximately constant with Mach number up to 5 (highest measured). A drop of Re/in from 3.4×10^5 to 0.9×10^5 increased the preceding ratio by approximately 40%. Laufer's extensive measurements should be interpreted in the light of the theoretical work of Phillips (Ref. 251) and Ffowcs Williams (Refs. 252 to 255) and the experimental wall pressure measurements of Kistler and Chen (Ref. 123). The mathematical structure of the theories in References 251 and 253 differs greatly, but according to Phillips his method gives very nearly the same answers when applied to the cases of Ffowcs Williams. In both theories the radiation pressure is proportional to the weighted mean of $\partial U/\partial y$, the mean shear of the sidewall boundary layer.

One could interpret this dependence and the above drop in p'/pM^2 with decrease in Re/in as a combined functional dependence on the turbulent skin friction coefficient, C_F, and the boundary layer displacement thickness, δ^*, (since $\partial U/\partial y \sim U_e/\delta^*$), and call these "aerodynamic noise parameters" at a given x, y, z location of the wind tunnel. Pate and Schueler (Ref. 2) conjectured that another length,

characteristic of the noise, would be proportional to the test-section circumference, c, - the "radiating belt length" at a fixed x. Utilizing the noise parameters C_F, δ^*, and c, they tried to correlate the Reynolds number of transition between a multitude of wind tunnels at Mach numbers from 3 to 8. They discovered that, as far as Re_{tr} was concerned,[12] the tunnel size had more of an effect than through c (the volume to radiating-surface ratio). By ingeneous usage of small and big shrouds in big and small tunnels they were able to extend the range of their testing of the tunnel size effect. Simultaneously they checked out the movement of transition and the trends in the intensity of sound inside the shielded shrouds, with and without tripping of the layer. The extra size effect led to the inclusion of a dimensional constant ($0.44\ C_1/0.56$ in the ordinate of Fig. 24, where $C_1 = 48$ in), a feature not clearly related to the noise processes.

The resulting correlation of Re_{tr} over flat plates and hollow cylinders from ten different wind tunnels across the 3-8 Mach range in terms of the aerodynamic noise parameters displayed in Fig. 24 is impressive indeed (c_1 is a reference tunnel circumference = 48 in.). Taken literally, it implies that transition in supersonic wind tunnels in this range is systematically dominated by the sidewall sound radiation, irrespective of Mach number or unit Reynolds number. Considering the variety of the transition phenomenon discussed in Section III, one could suspect Pate and Schueler of black magic. Part of the impact of their findings is administered to the reader in Figs. 25, 26, and 27. Figure 25 illustrates the inference that the major part of the unit Re effect in wind tunnels comes from the variations in the turbulent boundary-layer parameters C_F and δ^*. (Comparison with Fig. 13 indicates that Pate and Schueler too would have to cope with Softley's Mach 8 surprise of flat Re/in variation. The low-speed unit-Re sensitivity must also come from a different source-as one could expect in a different region of the phase space.) One implication of Fig. 26 would be that if one rendered the sidewall boundary layers laminar, the Reynolds number of transition would be Mach-number independent. However, the principle of dominant and multiple responsibility, PDMR, in Fig. 20 reminds one that removal of the front runner merely gives an opportunity to the next strongest disturbance to exercise its influence and impress its variation with its parameters on the process which is always unstable. According to the quotation from Kendall, one should expect Re_{tr} to go up substantially but its variation with Re/in may be anything - including the notorious 0.3 to 0.4 power. Similarly the Mach number variation could emerge non flat... For correlation of cones and implications, see Addendum 1.

An interesting check on the unit-Re effect was devised by Stainback, Fig. 27 (see discussion by Pate and Schueler in Ref. 2). Stainback recognized that at a given supersonic Mach number M_∞ the local edge-value of $(U/\nu)_e$ on a cone could be matched exactly on a "sister cone" with a different apex angle. The local paired Mach numbers, M_δ in Fig. 27, would of course differ but the radiating and receiving layers for the sister experiments could be made to operate

12. Pate and Schueler define x_{tr} as the location of the maximum in the wall pitot-pressure variation in x, i.e. near the end of the transition region.

at the same unit Re values. The results of Fig. 27 clearly support the M independence of Pate and Schueler (still in presence of the dominant disturbance). The authors in fact point out: "If a true Mach number effect on transition Reynolds numbers exists at supersonic and hypersonic speeds it appears doubtful that the trend can be established by comparing transition data at different Mach numbers obtained in wind tunnels having turbulent wall boundary layers because of the influence of radiated aerodynamic noise."

This is not the place to speculate on just how the sidewall noise causes transition (see Section III-5). Yet depending upon the many possible idealized models the effect could be rather local or, on the other hand, dependent on the integrated history of a traveling, sound-contaminated patch in the laminar layer.[13] In the early stages of development, it could be linear or non linear. Because of the approximate equality of the speed of propagation of the attacker, the radiating coherent eddy on the sidewall, and that of the T-S modes, the sound could even have some of the character of a forcing function, the attacker keeping in step with the victim. These comments have a bearing on the proper choice of the characteristic length of the interaction phenomenon. Pate informed the author that the choice of c is not necessarily sacrosanct and that he had elements of other correlations which could conceivably be as satisfactory as the present one.

The Pate-Schueler correlation has delivered its message of caution. The preceding speculative remarks merely underscore the fact that until the mechanism is better understood an element of uncertainty will remain as to the best correlating parameters. One would like to have them characterize the main links of the chain. Some links that appear to be dormant or missing are the transmission of the sound across the bow shock wave and its internalization by the boundary layer (receptivity of Section III-5). Judging by the Mack-demonstrated sensitivity of the T-S system to M (presumably related to receptivity), the inferred M independence of Re_{tr} is surprising unless it signifies a bypass of the linear systems. Furthermore, on the basis of the experience of Ref. 256 and 257 one could expect M changes in the transmissivity across the bow shock at the higher Mach numbers.

These comments aim at the practical question: Is it clear that the effect of the sidewall radiation will be as dominant and information concealing at truly hypersonic Mach numbers as it appears at lower Mach numbers on the evidence of Kendall and Pate-Schueler? The apparent rapid hypersonic rise of Re_{tr} with M (e.g. Fig. 29) may indicate lessened sound effect as a result of changes in one or more links of the total mechanism. The resulting Re_{tr} might be more acceptable as a practical lower bound for flight than in the Pate-Schueler range. See also p. 62.

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13. The interpretation of c as an intersection of the radiating sidewalls with the Mach forecone from the point of sound measurement would make c a "local" parameter. C_F, being a mean coefficient, averages over the length of the sidewall boundary layer starting at the nozzle, not over the growth distance of disturbances in the model boundary layer.

3. UNIT REYNOLDS NUMBER EFFECT IN BALLISTIC RANGES.

The much abused designation of results as "unique" applies deservedly to Potter's experiments in the AEDC Hyperballistic Range K, Ref. 3. First, they represent the only evidence of the unit-Re effect, Fig. 28, on a clean model without multiple characteristic lengths, the 0.005 in nose radius causing very little $p(x)$ and $S_e(x)$. Secondly they were so designed that the 20^o total-angle cones traveling at the high speed of 5700 ft/sec would arrive at any point on the range centerline before the sound radiation from the metallic walls of the range (caused by impact of sabots) would get there. At higher speeds, melting of the nose would compromise the experiment. Thirdly, following on the heels of the Pate-Schueler disclosures of the aerodynamic-noise felony (Section IV-2), Potter's exoneration of sound from complicity in the variation with unit Reynolds number of Fig. 28, had the quality of an insulin-shock treatment for the factious students of transition Doubting Toms can object to details of interpretation of this difficult experiment but it is hard to escape the following conclusions: (a) in absence of any significant free-stream disturbances, the Reynolds numbers of transition recorded in Fig. 28, at T_w/T_r of approximately 0.18 do occur in free flight at local Mach numbers near 4.4; (b) there is a variation with unit Re comparable to those in noise-contaminated supersonic wind-tunnels, Fig. 28; and (c) this variation is not due to external aerodynamic pressure waves.

The conceptual importance of the experiment undoubtedly warrants removing it from the uniqueness status by independent verification with special attention to the series of alternate susp[illegible]s proposed in the various discussions of Fig. 28 (e.g. Section III-9). The possible importance of unsteady internal stresses associated with the rigors of the launching were indicated by the following observation of Potter: "The first few cones had noses of copper alloy, and even though no surface discontinuity could be felt by hand before launch or seen in shadowgrams after launch, it was noticed that a weak shock wave always emanated from the joint between the copper and aluminum materials." Could the apex experience similar non negligible distortions, steady or unsteady? What variations in Re_{tr} could such distortions induce? Concerning roughness, Potter states: "Surface finish was around 10 microinches r.m.s., measured by use of a profilometer having a stylus tip radius of 500 microinches." The repeated concern, quoted in Section III-9, about characterization of roughness and of its role on highly cooled bodies at higher unit Re values, especially in the proximity of the cone tip may have to be met by the experimenters wanting to verify Potter's results. A role of the roughness which alone could account for the rising slope in Fig. 28 is hard to imagine.

In the language of Section IV-2, PDMR, Potter has removed the front-runner that dominated the transition race in wind tunnels. The shock of seeing essentially the same Re/L variation is perhaps salutory because it should help to educate the transition community to talk in terms of probability statements rather than deterministic laws.

When, at the same local Mach number of 4.5 over adiabatic flat plate, Kendall removed the same front runner in his wind tunnel (Section IV-2), transition, originally on the order one million vanished completely even on the tunnel walls where local Reynolds number exceeded five millions. Under those conditions, Kendall achieved the unique (sic) agreement with Mack's instability theory for both the first and second mode (Section III-4). It is then probably correct to expect an effect due to cooling comparable to those indicated by Mack's linear theory at these Mach numbers, especially when the model has been freed of the dominance by the front-running aerodynamic noise. Under the circumstances, Potter's line in Fig. 28, does not seem to enjoy the expected freedom from the spoiler sound and the beneficial effect of cooling - it appears to be low! It is hard not to suspect the presence of another, perhaps more sophisticated front runner distinct from Betchov's molecular-level excitation, Ref. 258, cited by Potter as a major suspect. The latter would make Re_{tr} high rather than low.

If the temperature-reversal trends of Sheetz' ballistic range experiments (Fig. 19) were present, the jig-saw puzzle could fit qualitatively much better, but that is of course no proof. Comparison with rocket-propelled flight tests of Ref. 212 might help if there were more detailed data. While the cone angle was the same and Mach number nearly so, the quoted Re_{tr} of 23 million may have been higher for other reasons. If the premise that Re_{tr} is insensitive to a change of total cone angle from 20° to 15° (apparently subscribed to by Potter according to his and Whitfields' Naples 1965 presentation, Ref. 105), the Rumsey and Lee's free flight, Ref. 220, provides a match of even unit Reynolds number:

Ref.	Me	Re/in 10^{-6}	T_W/T_r	Re_{tr} 10^{-6}	Nose rad.	Cone Angle
2	4.5	1.22	0.18	4.75	0.005 in	20° total
220	4.45	1.23	0.55	17.5	0.01 in.	15° total

The increase in the nose radius from 0.005 in to 0.01 in might bring Re_{tr} from 4.75 to perhaps 7.0 millions. The primary suspect cause for the remaining discrepancy of over 10 millions would appear to be the other obvious difference in T_W/T_r in presence of uncertain roughness and distortion conditions.

As was pointed out in Section III-9 the control of the experiment in the ballistic range is superior to that of a rocket-boosted free flight. The systematic information of Fig. 28 has no match in free flight. The cold reality of the data is not in question. The question is: can one make peace between these data and the previous information and concepts? It would seem to the present author that the molecular excitation, if relevant, should be present with and without sound and would have influenced Kendall's experiments as well. The apparent lack of response to the removal of the sound excitation implies a more powerful second runner. Potter's description of the ballistic range disturbances would seem to lead to some combination of the various

autodisturbances (Section III-9) including perhaps the (probably Re/L sensitive) hot-lip effect of Whitfield, Fig. 11, roughness in presence of cooling and relatively high unit Reynolds number, the stress and local-distortion sensitivity of the trip, etc. There ought to be a reason somewhere for the observed relatively early transition....

4. HYPERSONIC EXTRAPOLATIONS.

In the face of the erratic behavior of transition, n.b. that described in the preceding two Subsections and Sections III-3, III-5, III-6, III-9, it takes courage to assign variations to even the major control parameters - M, Re/L, T_W/T_r, nose blunting, yaw, etc. A young college graduate, steeped in the handbook-engineering tradition and blissfully ignorant of the Lessons from History and the price that may have to be paid for misestimates, will confidently wade in and generate yet another one of the correlative recipes for deterministic transition prediction. The careful hypersonic experimentalist, well cognizant of the risks and pitfalls, may also periodically put forward a public best-bet set of estimates, especially under contractual pressures. Since he knows more of the limitations of the information, he is probably the more logical source for such bulletins needed for design. However, such products of much effort and thinking might well still be stamped in large violet-ink letters: "Not to be used after Christmas 1970 without recheck with Dr. X." A more cautious designer would keep a folder wit' number of such current best-bet recommendations, together with a list of their acknowledged or identifiable limitations. He would weigh these qualifications when the time of decision comes on his project and then make his ad hoc best-bet estimates, with one eye on the risks of possible deterioration of performance caused by misestimates.

A fair sample of the experimentalist-generated public view of hypersonic transition is found in Figs. 29, 30, and 31 of Softley, Graber and Zempel, Ref. 109. The desirability for some placard warning the USER to proceed at his own risk, was underscored by the dramatic Mach 8-9 change in the anticipated variation of Re_{tr} on their sharp 10^{o} total-angle cone with Re/L, obtained after their views were first formulated - see Section III-5 and Fig. 13. From the information in Fig. 13, the effect of local Mach number on (beginning, subscript $_B$) transition Reynolds numbers in Fig. 29 was obtained "by assuming that the data obtained at the same unit Reynolds number in different wind tunnels are comparable. There is, however, no physical argument to substantiate this step. Hence Fig. 29 should be regarded with caution. No significance to the exact trend can be assumed until the phenomena (sic), Unit Reynolds number, are understood." That is a clear warning the designer should not forget. The Mach 8-9 data violate the assumption.

The authors are much less cautious about the T_W/T_r effect: "It is concluded that variations in the wall-temperature ratio do not affect transition...." This confident statement is based on a number of low Re/L experiences in hypersonic wind tunnels, where the aerodynamic noise may be masking other variations. The evidence for a hypersonic T_W/T_r effect comes from impulse-type tests, as remarked in Ref. 145, which incidentally simultaneously sport high unit Reynolds numbers. Since many vehicles will perform at higher Re/L than testable in hypersonic wind tunnels, the designer cannot dismiss the temperature reversal from consideration. On the basis of evidence such as in Figs. 13 and 29, some courageous engineers have been extrapolating the

rising curve in Fig. 29 with a M^4 approximation which would correspond to very powerful stabilization at hypersonic speeds. Clearly, the evidence is very limited and caution should probably match the courage. Reliability of the information is almost impossible to assess. However, risk studies in connection with each design are desirable.

Other observers with a finger on the pulse of hypersonic wind tunnels will semi-agree, Ref. 145, or quite disagree, Ref. 110, with the premises and interpretations of Fig. 29. The innocent practicing engineer will probably be grateful for any such extrapolation and guidance.

Figure 30 illustrates the more complicated trends of the variations of the coordinates of Fig. 29 for increasing nose blunting, indicated by the ratio of the transition location, X_B, to the swallowing distance, X_{SW}, see p. 24. Even without yaw, a number of effects coexist as a result of the blunting, as has been discussed in Section III-5. As the blunting increases, the swallowing distance also increases, but the axial distance to transition (from virtual apex) increases even faster so that the Reynolds number of transition departs upward from the sharp-cone curve of Fig. 29. In a sequel to Ref. 109, Softley (Ref. 345) generalizes from Fig. 30 and the recomputed data of Ref. 108 to the effect that, at a given free-stream Mach number, the maximum attainable Re_{tr} due to blunting of slender cones at hypersonic speeds is approximately twice the sharp-cone value of Fig. 29 (i.e. slightly below the $X_B/X_{SW} = 1$ curve of Fig. 31). He also states that local Re_s (based on wetted length) and M_e alone "are insufficient to obtain a correlation of blunt-cone transition at high free-stream Mach numbers". The innocent practicing engineer will have difficulties reconciling the preceding observations with the extensive ballistic-range data of Sheetz, Ref. 231, for slender cones with half angles of 3, 6.3, and 9 degrees, see Fig. 19 for a sample. Besides the obvious differences in the environmental effects - Re/in, T_W/T_r, free-stream disturbances, roughness, etc - there are differences in the manner of computing the local values of the complex flowfield and of the nonsimilar boundary layer, which appear to contribute to the differences in interpretation. (See also Ref. 110 for discussion of the entropy layer computation.) Interestingly, no clear beneficial effects of blunting manifest themselves in the relatively wide range of parameters tested by Sheetz in the NOL Ballistic Range.

For some sizes and shapes an analog of the contamination of the flow along the leading edge of a swept back wing by turbulence from the fuselage may occur. Because of the lesser stability at lower Mach numbers, transition might develop in the region of the body, say for $M < 4$. This would constitute a finite disturbance in the sense of Coles (Section III-6, p. 32 and Ref. 162) for the much more stable high-Mach-number boundary layers downstream. Under such circumstances an early transition could take place because the layer, though normally stable, might not be able to cope with the extra high excitation from upstream. Figure 31 shows the actual local-condition trajectories experienced along a medium blunted and a sharp 10° total cone in the G. E. Philadelphia shock tunnel with a contoured nozzle and along a sharp cone in the sister G. E. Schenectady facility, with a conical nozzle. One sees that because of the non zero axial pressure gradients M_e along the cones is not a constant, especially not so in the Schenectady facility. There, the relatively high Reynolds number over the front part of the body makes the facility ideal for observation of the "low-M contamination" effect. According to Softley et al: "The beginning of transition as quoted for the Schenectady facility agrees with the transition Reynolds numbers shown in Fig. 29 at

local Mach numbers about 10 but produces much lower transition Reynolds numbers at higher local Mach numbers. This is almost certainly a result of the severe axial gradient of Mach number and pressure in that conical flow facility." Should such a contamination occur over shapes in flight the motion of the transition could be expected to be discontinuous.

The low-M contamination almost certainly takes place on the sidewalls of hypersonic wind-tunnels and thus causes the severe acoustical environment. Attempts to thwart the turbulent sidewall boundary layer are being currently made in several facilities. It would seem that "blowing off the full layer" at the location where $M \sim 3$ or 4 (i.e. having a bypass to the point of low pressure) could well protect the downstream more stable sidewall layers. In effect, the sidewalls past the BL diversion station would constitute a variable-M Pate-Schueler shroud, on the "inside" of which the boundary layer would have a better chance of remaining laminar throughout the rest of the journey to the hypersonic Mach numbers. Efforts toward laminarization of at least one truly hypersonic wind tunnel should be continued even in the face of possible initial setbacks. In such a tunnel the question raised at the end of Section IV-2 concerning the possibility of lesser noise degradation of Re_{tr} past Mach ten or so could be settled for the whole class of tunnels. If so, the extrapolation of estimates to yet higher Mach numbers could proceed with somewhat more confidence than at present.

SECTION V

DESIRABLE RESEARCH AND DEVELOPMENT

It would be presumptuous for anyone to compose a list of suggested experiments for different high-speed facilities. One may educate oneself to become a constructive critic with respect to such facilities but only the local practitioners know their tools well enough to propose a program optimally suited to their facility. The monograph was purposely written in a manner which might challenge the experimenter and the theoretician to exercise their ingenuity in resolving the abundant question marks on their own virtuoso instruments. In fact, in rereading the manuscript the author got several new ideas for potentially significant experiments in his own bailiwick. Practically every time there is a statement like "Don't know" or Don't understand" one can ask "Is it important to know?", "What features suggest which approach?", and thus compose for oneself a private list of possible research objectives.

Recalling the state of mind described in the Introduction, it would seem that there could be two complementary policies for supersonic and hypersonic transition research. One would aim at better understanding of the several mechanisms of instability and breakdown and the other at an early improvement in the capability of estimating the lower and upper bounds of the probable location of transition. Clearly, both policies would wish to define and improve the disturbance environments in the ground facilities. Since theory is the cheapest tool, both policies would favor extensions and penetrating exploitation of instability theories. Mack's systematic mapping of the supersonic instability landscape and Kendall's decisive experiments show how illuminating a cooperative approach can be. There should be an organized nationwide cooperative effort in determining and improving the limitations of the twin tools of linear theory and of our ground facilities. Without organized cooperation, the practical open questions of Section IV are unlikely to find even partial answers in a reasonable time span.

Section IV-1 sketched out a framework of concepts within which the theoretical and experimental evidence and perhaps even design questions could be approached more systematically. Practically every entry in Fig. 20 has a research question associated with it. For a particular regime of applications the existence or non-existence of bypasses of the Linear Box in Fig. 20 appears crucial with respect to the rational utilization of theory. One recalls the early transition phenomenon on blunt bodies, $Re_{\theta tr} \sim 150$ to 250, as an example where there appears to be an as yet unidentified bypass (probably associated with the interacting effects of roughness, cooling and pressure gradient). Are there other such bypasses in the range of operational parameters of a given design? For instance, for vehicles designed for operations at high unit Reynolds numbers, do the phenomena of temperature reversal in high impulse facilities and of unit Reynolds number effect in the ballistic range presage a bypass and earlier transition? Would the bypass be enhanced or inhibited by the presence of ablative emanation $\dot{m}$ from the surface?

For given external conditions, a specific roughness element might lose effectiveness as $\dot{m}$ increases and envelops it with slower moving mean flow. The resulting changes in Re_{tr} have been evocatively characterized as occurring in a different region of the phase space of the controlling parameters in order to emphasize that sensitivity to roughness may change when another parameter varies. The concept of phase space should help to avoid the sterility of arguments that took place with respect to hypersonic temperature sensitivity and to focus on the differences in the parameters as a clue to the causes of the different observations (e.g. Reshotko, Ref. 79). The actual dimensions of the space have been left purposely vague. They should vary from case to case depending upon the ranges of the major parameters. One always looks for the smallest number of dimensions the given phenomenon will permit. In a given test or experiment, both the objectives of better understanding and of better Re_{tr} bracketing are advanced more rapidly when the phase-space neighborhood of observed sharp changes in slope of the Re_{tr} surface is systematically explored. It is highly desirable to "perturb", preferably one by one, all the other controllable parameters in that vicinity and thus obtain the sensitivity of the more singular (rapid) behavior of the transition surface to these variables. From information about such more singular behavior, conjectures (and their verifications) concerning the underlying mechanisms are more likely to follow. In particular the burning questions of temperature transition reversal and of the role of very small roughness in presence of cooling at high unit Reynolds numbers could be explored to advantage in this manner. The presence of downstream contamination effects (Section IV-4) should not be overlooked as a possible contributor to the rapid changes at high Mach numbers.

In absence of bypass paths in Fig. 20 (for a given range of parameters) much needs doing in order to make the linear instability theory a viable tool for judging what constitutes "normal behavior" in presence of multiple instability modes and multiple parameters. The contrast between any observed growth of disturbances (and its documented dependence on various parameters) and their theoretically expected standard growth and behavior is a key to better understanding and rational correlations. At present even the "complete 2D T-S stablization" limiting surface: $M(T_w/T_r, Re)$ for which the first 2D mode is quenched (zero amplification) p. 16, remains a vague shape at best and is of little help in assessment of experimental data. The earlier recommended explorations of the $p(x)$, $p(z)$, and $\dot{m}$ effects in the box of Modifiers in Fig. 20 appear essential for ultimate rational interpretation of transition in flight. However, before one can approach the instability problem proper, one has to have tools for computing mean boundary layer profiles for the specific pressure and mass transfer conditions of interest, preferably with different degrees of cooling (e.g. Ref.112). This is also true for real-gas effect which at first will be felt primarily as a mean BL Modifier. Early conversion of the theoretical instability results into forms understandable and usable by people not versed in the theory would be commendable.

The ground work for stability calculations in presence of transpiration has been laid by Shen, Powers and others in Ref. 259-262. Published experimental information on instability or transition with mass transfer does not permit many conclusions at the present time. The reader is referred to Refs. 264 and 272 for disquieting inferences and to Ref. 265 for solace in the mildness of the observed effect. He is offered Pappas and Okuno's Ref. 263 and borrowed Figures 32 and 33 as a challenging evidence that the nature of the gases emanating from a wall has strong influence on even the character of transition. It is clear that for the same relative injected mass flux, $F = (\rho v)_w/(\rho u)_e$, helium has a much stronger effect than air. On the other hand, the succession of the intriguing, apparently three-dimensional non linear waves in the top segment of Fig. 32 is not yet reflected in any measured change of heat transfer at the wall. The danger of expecting the transition behavior to be unique is clearly illustrated in this figure.

The peculiar formations in the air-helium transition serve to remind one of how little is known of the breakdown and especially of the transverse contamination as a function of Mach number. One can only echo Lees' call for good microscopic measurements in good wind tunnels (see Introduction) both with respect to the instability processes as well as the transition phenomenon itself.

At really high Mach numbers, the loads and heating of probes are detrimental to carefully calibrated experiment so that the burden of microscopic measurements will probably shift to helium wind tunnels. In fact, the helium tunnels are beginning to furnish the first glimpses of the structure of turbulent layers at Mach numbers above 15. As remarked earlier, it is good to have an idea of what the ultimate evolution of the layer is likely to be in order to anticipate the three-dimensional reorganizational requirements met in the transition region.

The various uncertainties described in the body of this report and the additional remarks of this Section should make clear the magnitude of the problem. Unless the scope and intensity of the national research effort is commensurate, the pessimism described in the Introduction will be justified.

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VII ADDENDA

1. ANOTHER OPEN QUESTION: CONE VS. FLAT PLATE

One task of a rational guide to prediction of transition must be to establish a relationship between Re_{tr} of the two simplest, constant-pressure bodies - a cone and a flat plate, with identical constant M_e and T_w/T_r conditions. Through the Mangler transformation (Ref. 285a) the two boundary layers are related in such a way that at the same Re_x the plate boundary layer is $\sqrt{3}$ times thicker than the cone boundary layer. Hence Sternberg (Ref. 16) concluded that observing a laminar layer at Re_x of 90×10^6 on his V-2 nose cone was equivalent to observing a laminar layer on a flat plate at Re_x of 30×10^6. No comment could be made about the relative level of amplified disturbances at these two comparable mean flow conditions. Since at some distance from the tip region, the usual linearized stability equations for the cone and the plate are identical (quotations from Tollmien and Mangler in Ref. 279). Using linear theory Battin and Lin (Ref. 344) connected the amplification rates in the two boundary layers and concluded that the upstream points of zero T-S amplification for any given frequency are related by $(Re_{x_{cr}})_c = 3\,(Re_{x_{cr}})_p$. Many have inferred that the same relationship should be valid for Re_{tr} as well.

Tetervin, in a little known paper (Ref. 281), pointed out that if one adopts the Liepmann criterion (Ref. 28) that the Reynolds stress of the still linear T-S fluctuations reaches the level of the maximum mean laminar stress just before transition, an estimate of the cone-plate Re_{tr} relation could be made on the basis of linear theory alone. (See also Ref. 318 for low-speed predictions based on Ref. 28, linear theory and correlations.) In that pre-computer, pre-Mack era, Tetervin had to make some strong assumptions in order to utilize Schlichting's available incompressible amplification rates and conclude that $(Re_{x_{tr}})_c = (Re_{xtr})_c + 2(Re_{xcr})_p$. He added: "The analysis indicates that the (cone-to-plate Re_{tr}) ratio varies from 3 when transition occurs at Re_{cr}, to unity when transition occurs at a large multiple of Re_{cr}." Even if his many assumptions were approximately correct, the free stream disturbances, their transmission across the cone shock, and their assimilation into the two boundary layers (of different lengths!) would undoubtedly influence the relationship. The analytical framework assumes in fact that disturbances are all assimilated upstream of the respective Re_{cr} locations, yielding their equal "starting" amplitudes, and that no further disturbance input occurs thereafter. Furthermore, leaning on the 2D incompressible results, the analysis cannot reflect the known presence of Mack's higher T-S modes nor of the more unstable skew waves.

In view of the scatter of Re_{tr} values some correlators could and did convince themselves of the usefulness of the simple "theoretical" factor of 3. Whitfield and Ianuzzi's recent collection of wind-tunnel and ballistic-range data (solid symbols - extrapolated to the same unit Reynolds number of 0.3×10^6 in.$^{-1}$ for comparison purposes) over a wide spread of Mach numbers is reproduced from Ref. 145 in Fig. 23 herein. They concluded that "comparison of ... the data reveals a confusing picture concerning the relationship of cone and flat-plate (hollow-cylinder) transition Reynolds numbers. It is no longer clearly evident that experimental cone transition Reynolds numbers are greater than the flat-plate values, even at moderate supersonic Mach numbers". However, Fig. 23 suggests nevertheless that at higher Mach numbers such as eight, the cone and flat-plate transition distances approach each other, as noted earlier by Potter and Whitfield, Ref. 105.

In a preliminary unpublished report Pate and Schueler describe the follow-up of their systematic experiments on hollow cylinders in wind tunnels of various sizes, Ref. 2, with similar tests of sharp cones of 10° total angle. Concentration on $M > 3$ wind-tunnel data alone, of course, focuses the attention on the tunnel unit-Reynolds number effect and its possible dominance by aerodynamic sound. The new cone information together with data from ten other sources and facilities appears to follow reasonably well a correlation similar to that of Fig. 24, namely $Re_{tr} = f(C_F, \frac{\delta^*}{e}, \frac{e_r}{e})$, i.e. is again independent of M and Re/in. In fact, Pate and Schueler change only the coefficient 0.0141 to 10.5 and the logarithmic slope of C_F from -2.55 to -1.66.

One implication of the latter change would be that, exposed to the same free-stream Mach number and aerodynamic noise, the cone boundary layers respond differently to the disturbances than do flat-plate boundary layers. Unless such an effect is at least qualitatively understood in terms of the aforementioned "rational guide", what can justify hopes for correlating transition locations over a really significant sample of tunnel information for practical bodies over which pressure varies in x and z (or θ)? And if such a correlation could be gleaned, what would it mean with respect to transition in flight?

Pate and Schueler tentatively conclude that the ratio of cone $(Re_{tr})_c$ to flat-plate $(Re_{tr})_p$, in wind tunnels, is approximately 2.4 at Mach 3 and that it decreases monotonically with M to a value slightly larger than 1.0 at Mach 8, with some dependence on tunnel size between Mach 3 and 5. Many a reader would be tempted to compare this result to the quoted statement of Tetervin. However, any satisfactory explanation of such temptingly simple law must take into account the comments immediately following the quotation from Tetervin.

2. DISTURBANCE ENVIRONMENT IN FREE FLIGHT

The call for determining the disturbance environment in the various testing and research facilities has been repeated like a refrain by the transition experts concerned about the obviously major role of the fluctuation input on the occurrence of transition. There is little information on the corresponding disturbances in flight, especially at altitudes above those used by commercial airlines. The altitudes of special interest to supersonic and hypersonic vehicles are being studied under projects HICAT (High Altitude Critical Atmospheric Turbulence 40,000 - 70,000 ft.) and HI-CAT (70,000 - 200,000 ft.), directed by the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio (Ref. 273), in cooperation with other U. S. and Canadian institutions and agencies.

Actually, the global nature of the atmosphere fosters much international cooperation and some of the most definitive statements on turbulence at high altitudes have been made by "working groups" at two such international Symposia (Refs. 274 and 275). These altitudes are not as free of turbulence as might be expected; nor are the scales of turbulence and density fluctuations obviously too large to definitely exclude the possibility of the fine-structure tails of their spectra to retain enough energy and induce structural and aerodynamic responses of hypersonic vehicles. Apparently, the energy input into the potentially dangerous spectra is associated with the dynamics of relatively narrow atmospheric layers within which density and winds undergo rapid changes. Thus, any disturbances of consequence are likely to be met by the vehicle in "patches", sporadically distributed in time and space. Any probability statements concerning the distribution, intensity, and scales of such patches must await much research which is very indirect in altitudes beyond the reach of U-2 aircraft. As an interim working hypothesis, the author would propose the assumption that the distribution, the intensity and the scales of such disturbance patches are no worse than at the MEDCAT (20000 - 40000 ft.) and the HICAT altitudes (disregarding the disturbances of cumulonimbus clouds), concerning which the necessary information is rapidly accumulating.

The velocity fluctuations and density spottiness in the atmosphere (just as in the aeroballistic range) are transformed into the direct disturbances impinging on the vehicle after a nonlinear interaction with the bow shockwave. Thus, even though no relevant sound disturbances are expected in the atmosphere itself, pressure fluctuations, always generated in such interactions (Refs. 256, 257), as well as vorticity, temperature and density fluctuations would constitute the direct input to the boundary layer of the vehicle. The frequency spectra are obtainable from the "free-stream" scale distribution by division by the velocity of the vehicle.

ADDITIONAL REFERENCES

For the present concept-oriented concise review the references were chosen for their direct relevance to the points under discussion rather than for the sake of historical completeness. Many more papers and reports than were cited in the first draft of the review had actually been consulted. The student of transition would be shortchanged if some of the important and influential contributions, e.g. Schlichting (Ref. 285), Lees (Ref. 286), and Lin and Benney (Ref. 288) were not referenced herein at least broadly rather than specifically. He will find many additional leads in these references as well as in Refs. 1, 10, 13, 14, 24, 27, 30, 32, 33, 46, 48, 56, 85, 86, 105, 133, 134, 140, 145, 148, 188, 226, 233, 234, 273, 274, 275, 285-293, 311, 312 and 318. The added references again relate primarily to high speeds. For some of the latest exciting theoretical and experimental developments in the low-speed domain the reader is referred to Tani's review, Ref. 56, and to the report on the1968 NATO Advanced Study Institute in Transition, Ref. 27.

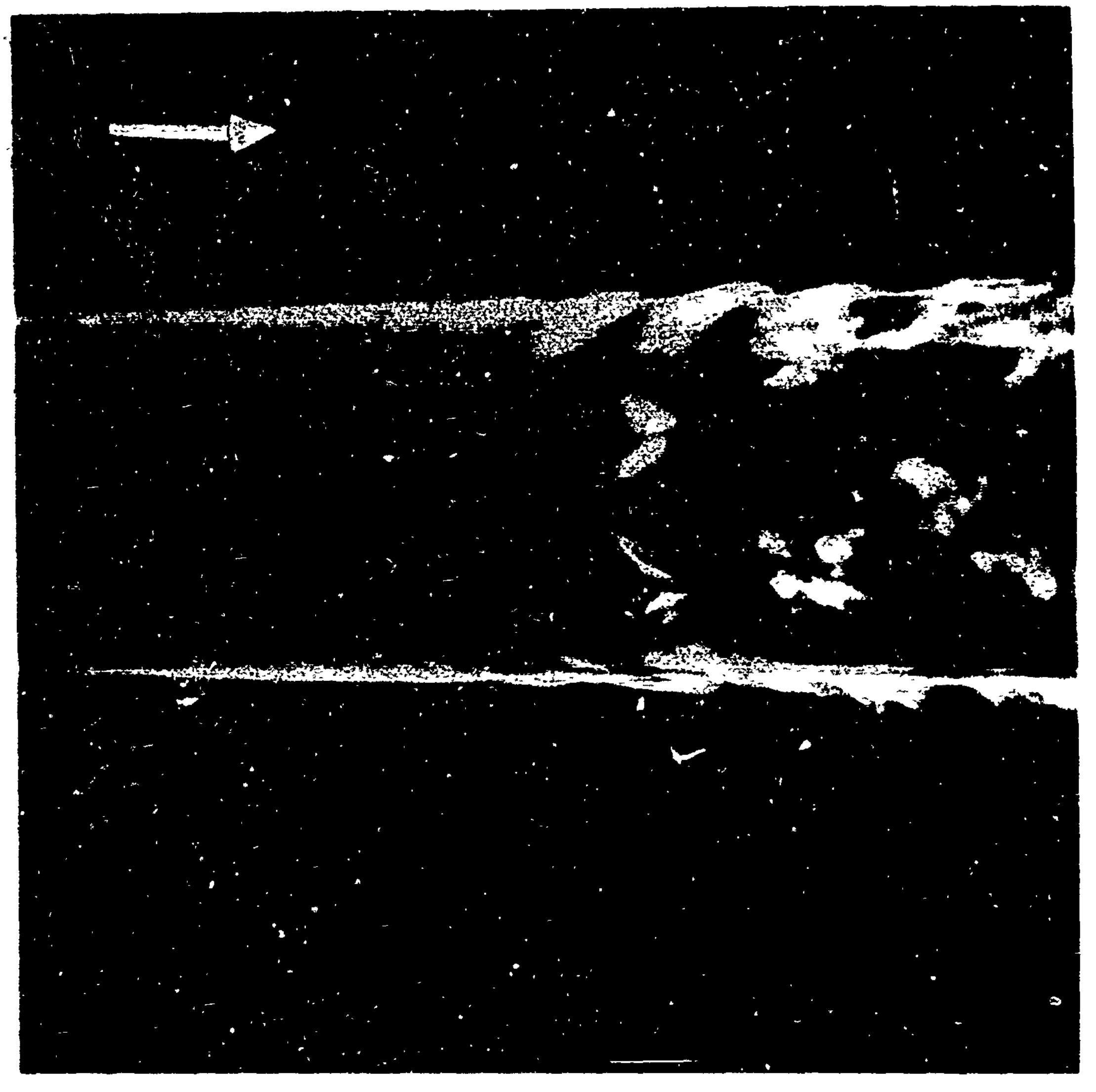


Fig. 1 - Three-Dimensional Deformation of a Smoke Wave in Zero and Adverse Pressure Gradients

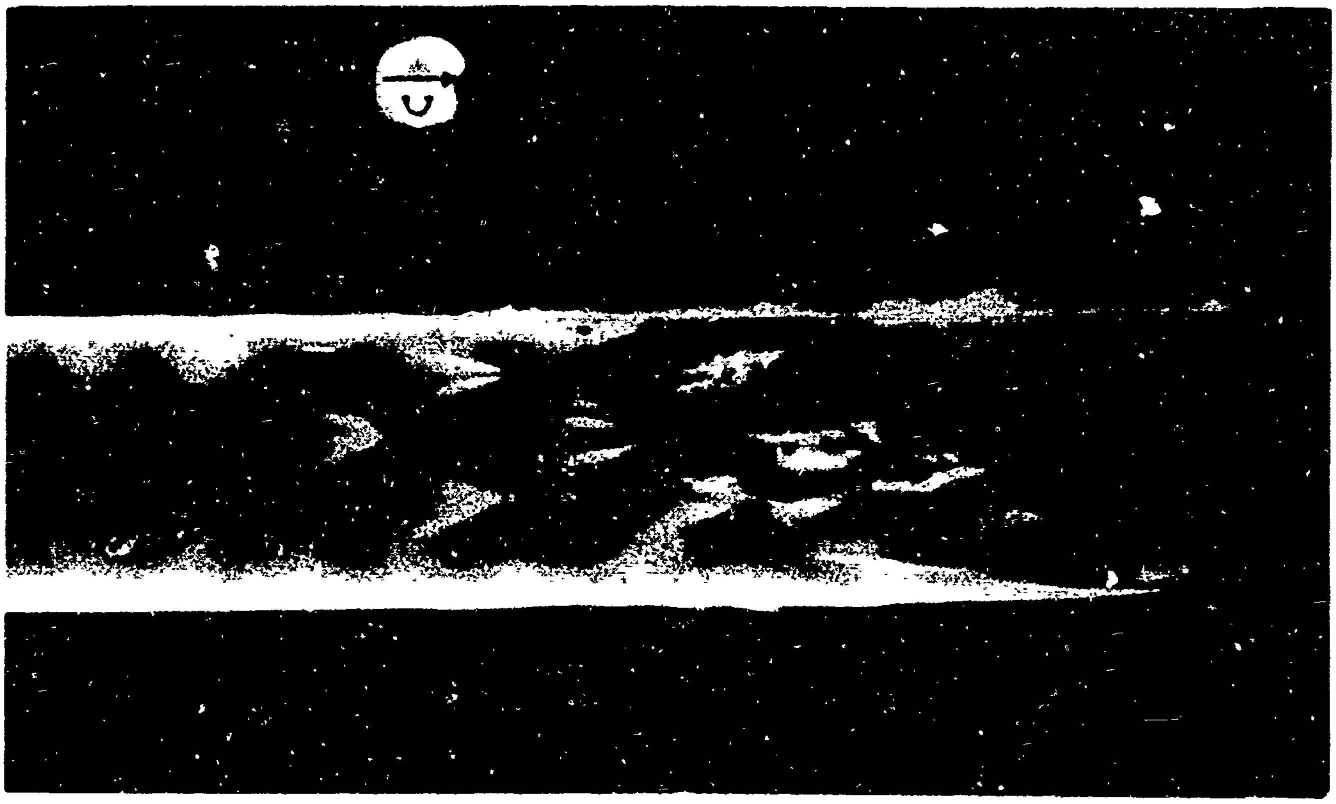


Fig. 2 - Region of Vortex Trusses and Breakdown in the Zero Pressure Gradient

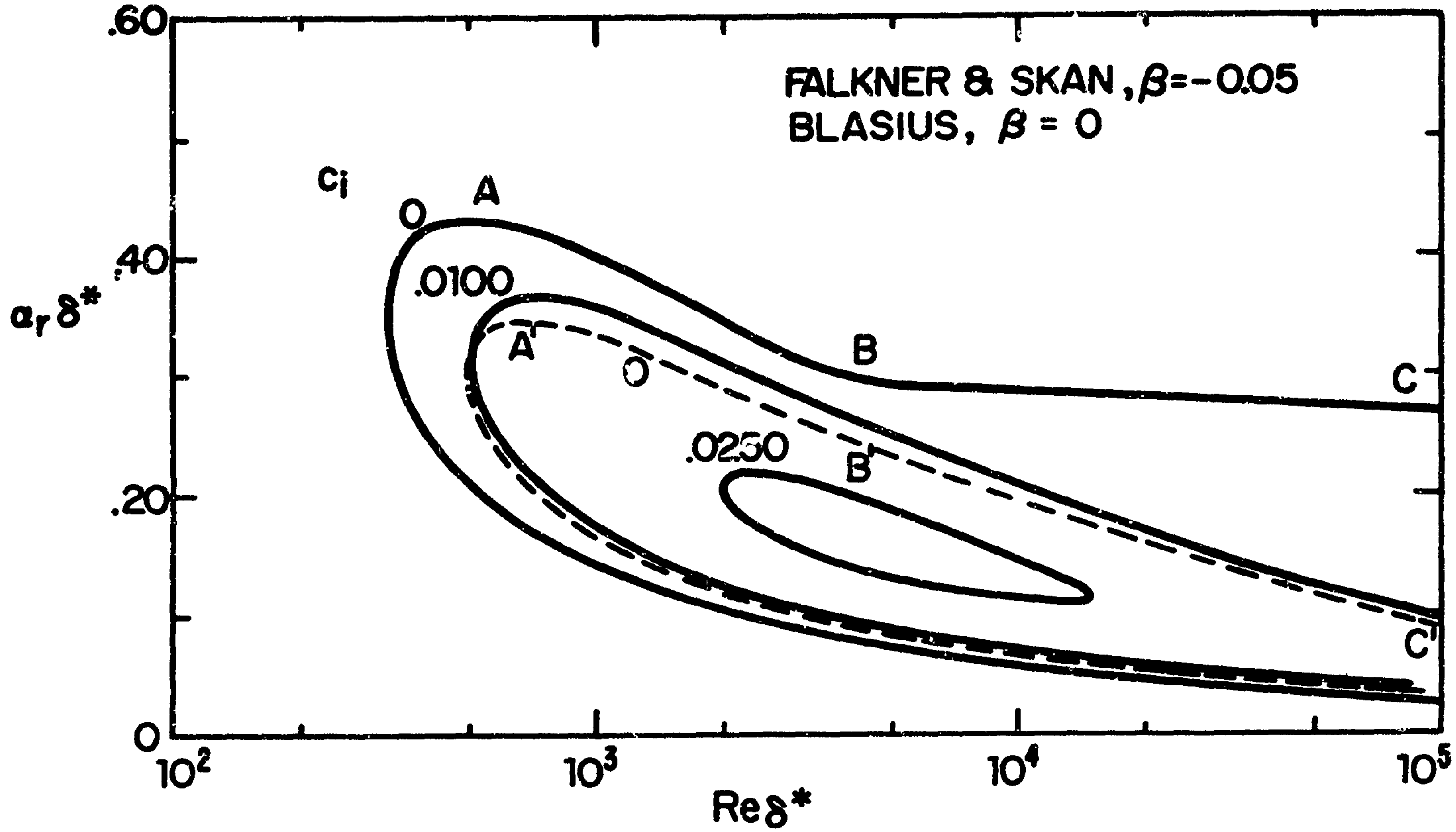


Fig. 3 - Shift From Viscous To Inviscid Amplification At Low Speeds

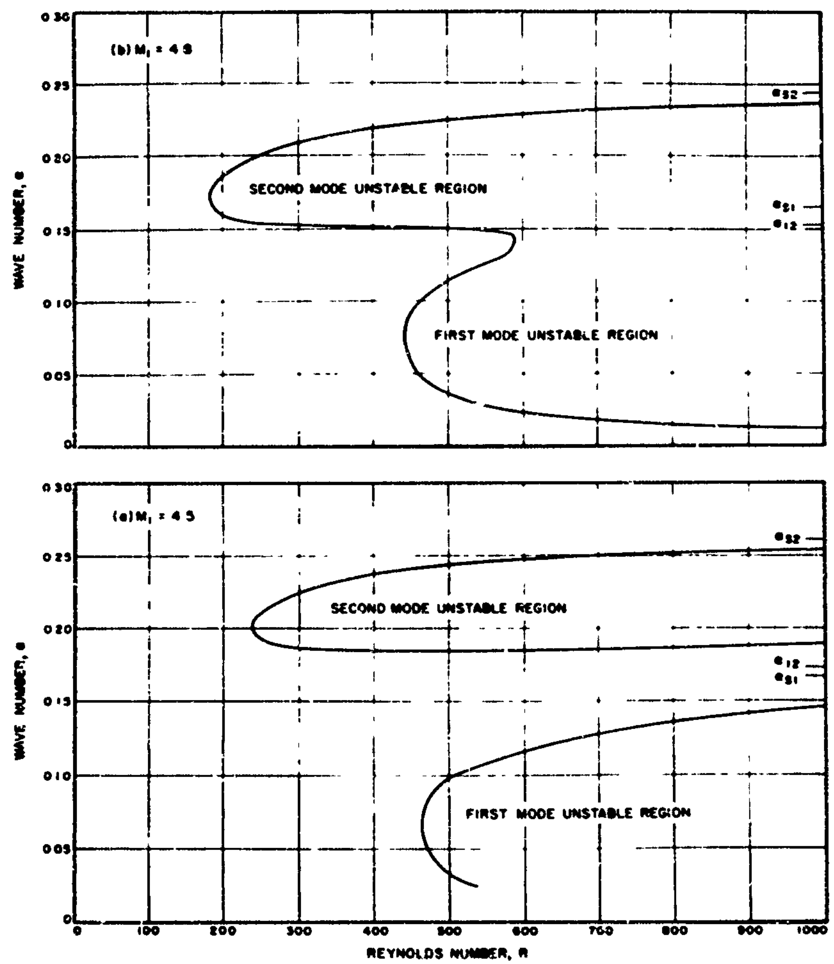


Fig. 4 - Neutral-Stability Curves Of Wave Number Vs Reynolds Number For Insulated-Wall Boundary Layer Near Mach Number At Which $\alpha_{12} = \alpha_{S1}$ (a) $M_1 = 4.5$, (b) $M_1 = 4.8$

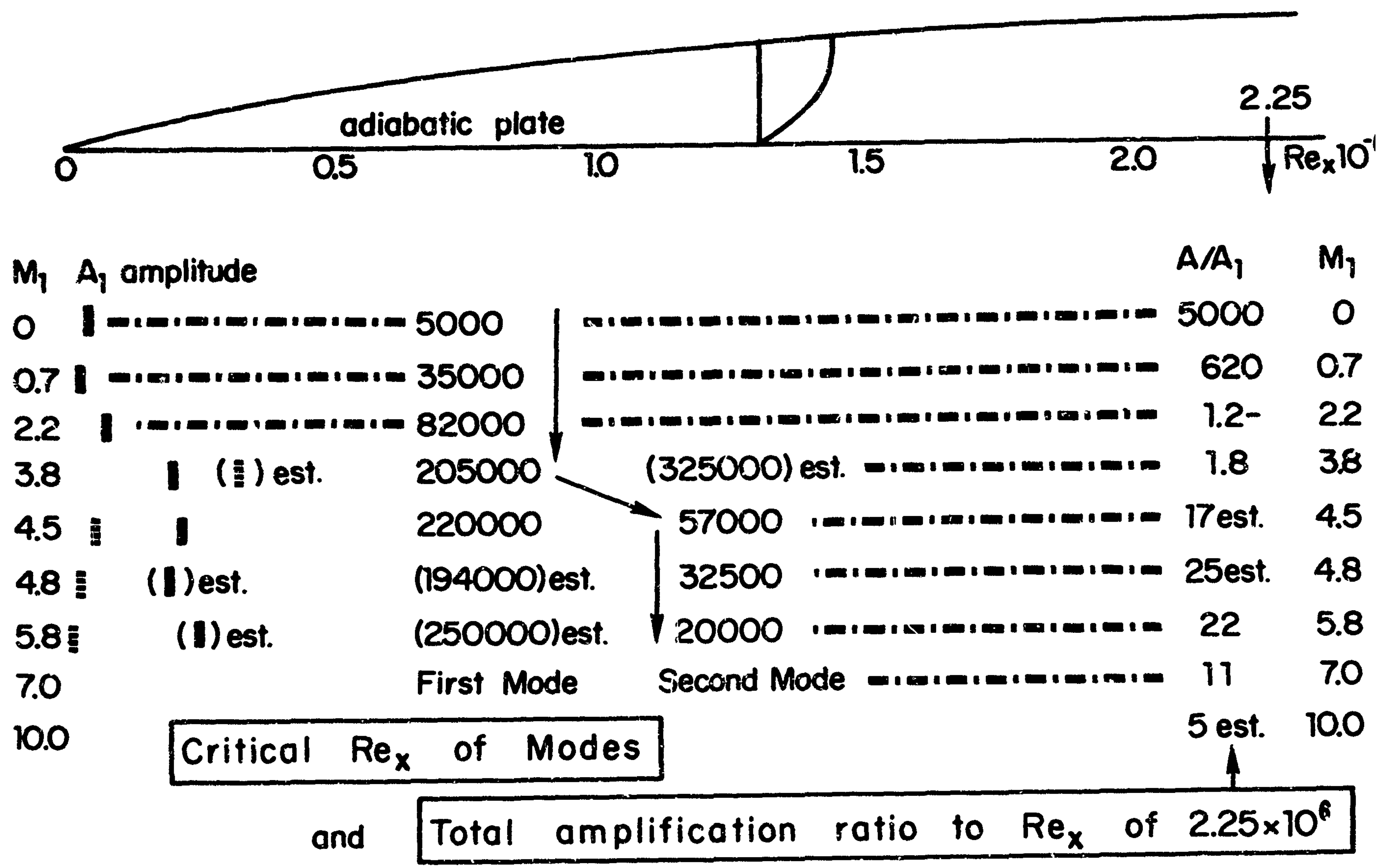


Fig. 5 - Critical Re_x Of Two Dimensional Instability Modes And Total Amplification Ratio to Re_x to 2.25×10^6

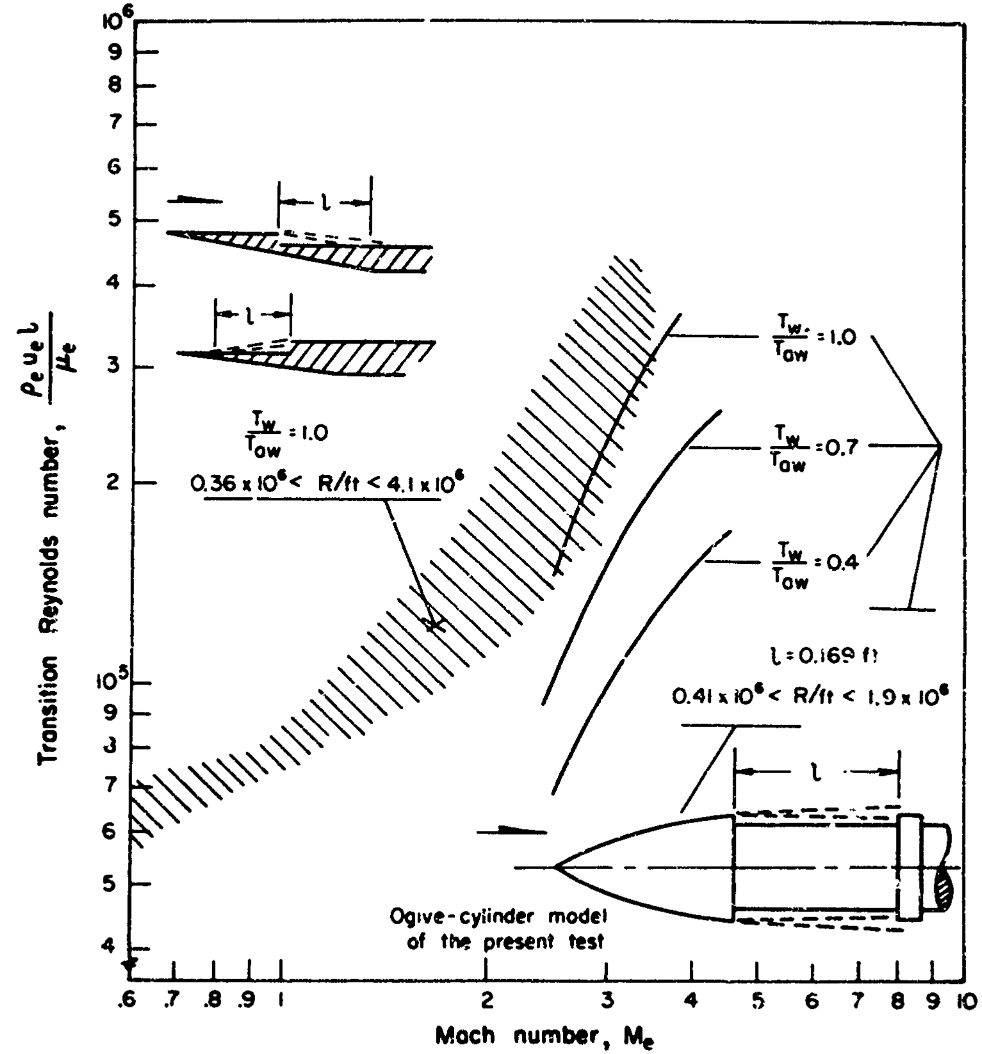


Fig. 6 - Comparison Of Transition Of Separated Axisymmetric And Two Dimensional Mixing Layers

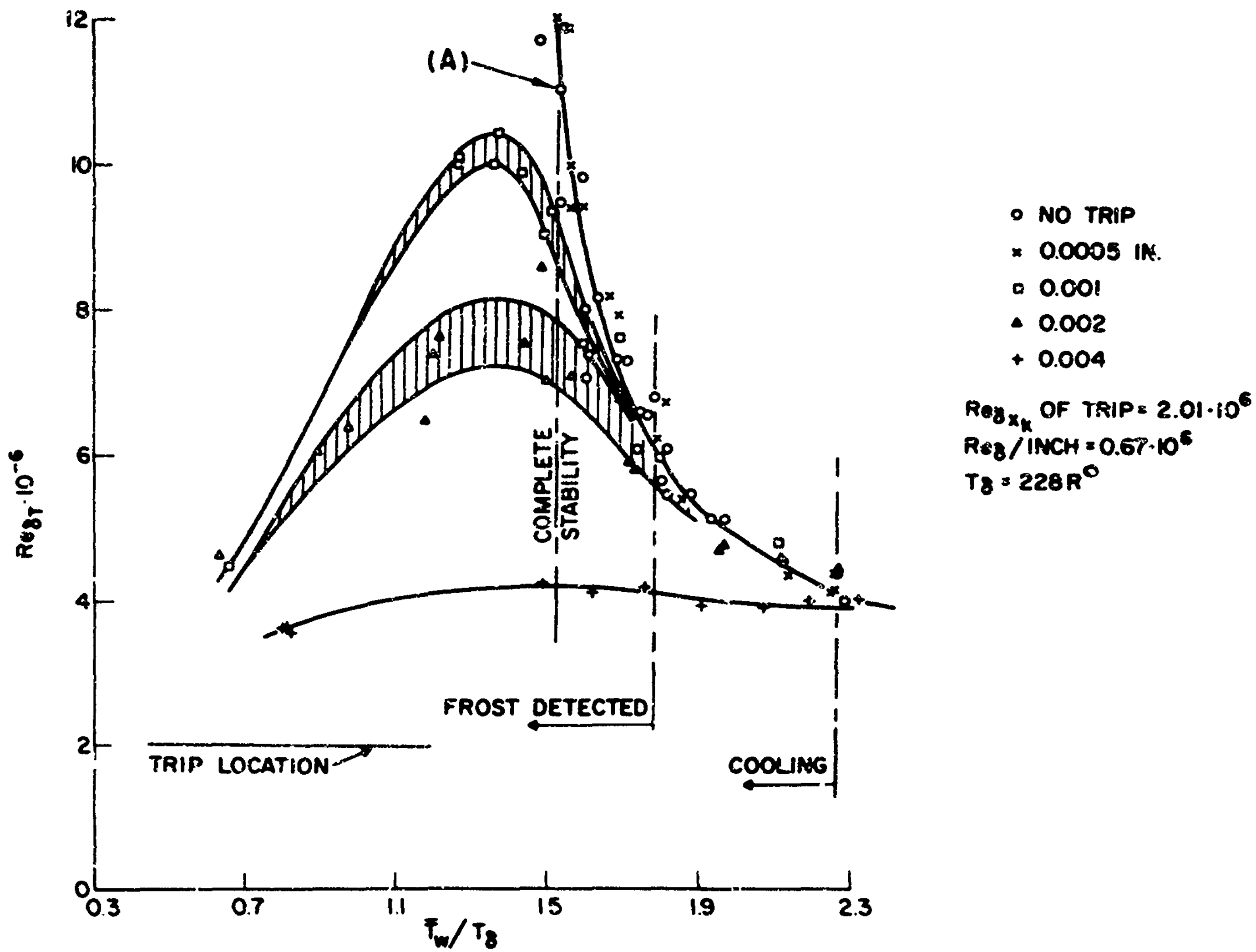


Fig. 7 - Effect Of Roughness On Transition With Cooling.
$M_\delta = 2.70$, 20-in. 10° Cone.

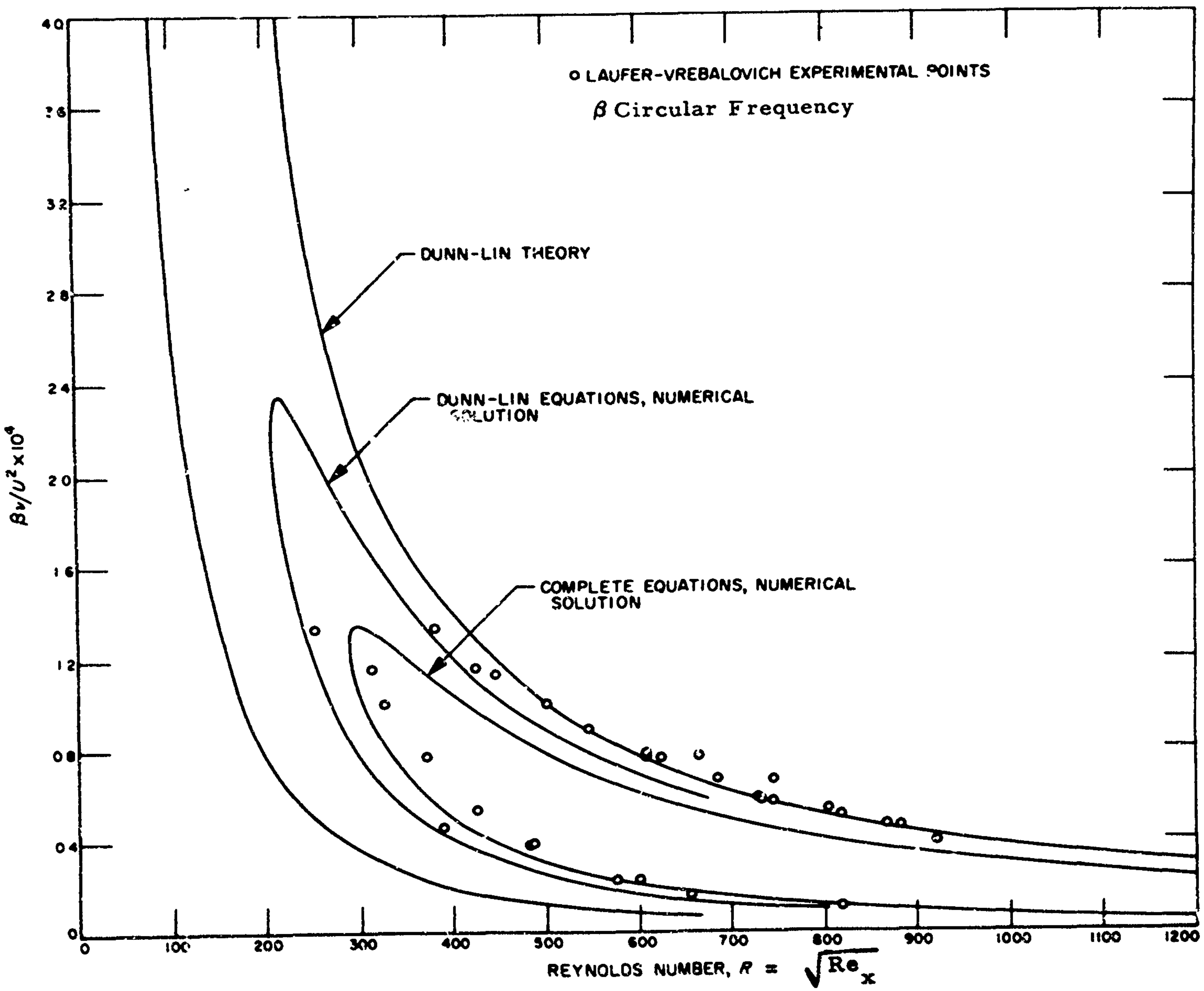


Fig. 8 - Neutral Stability Curves Of Frequency At $M_1 = 2.2$

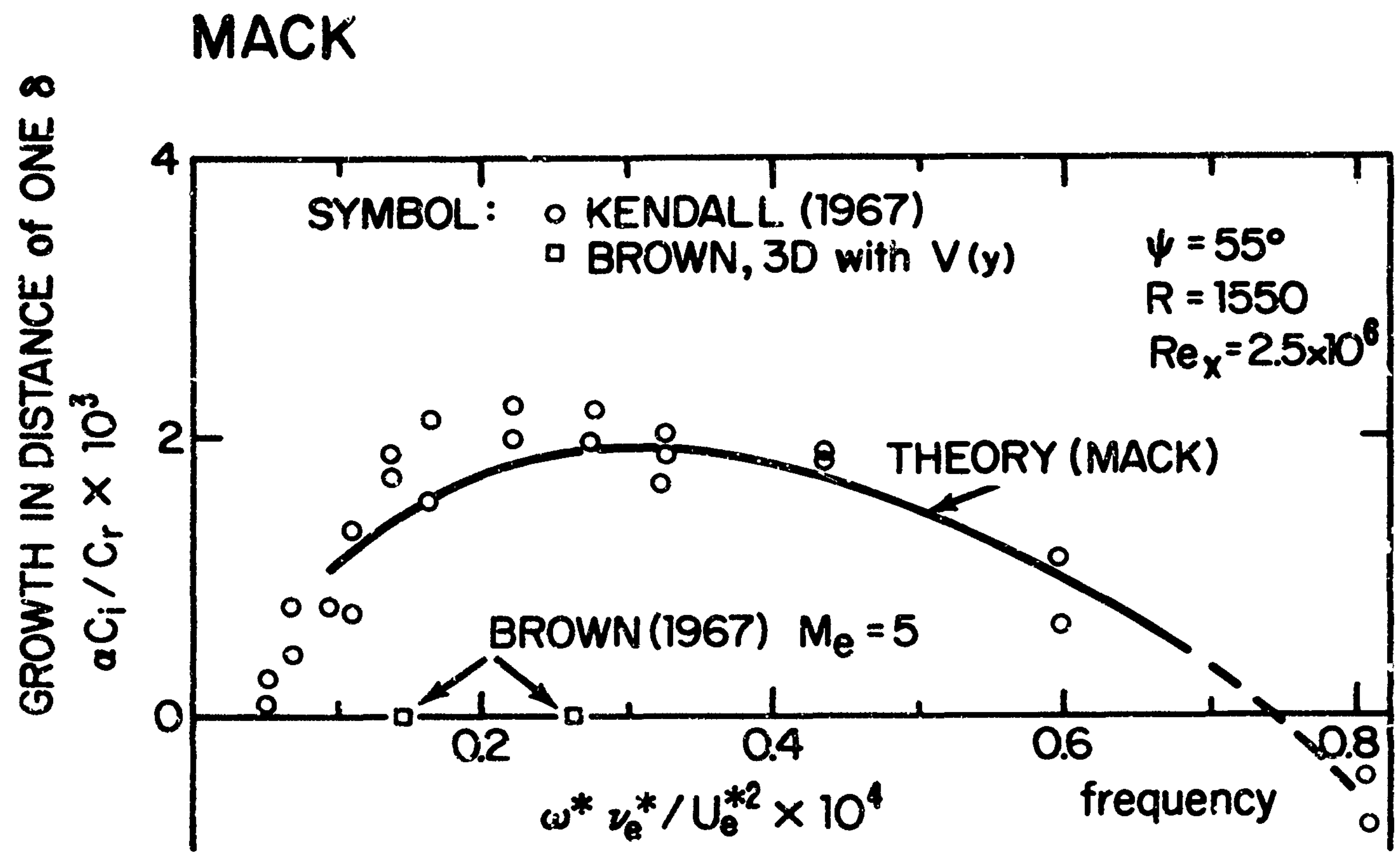


Fig. 9 - Comparison Of Calculated First-Mode Spatial Amplification Rate At M_e = 4.5 For 55° Wave With Measurements Of Kendall (1967)

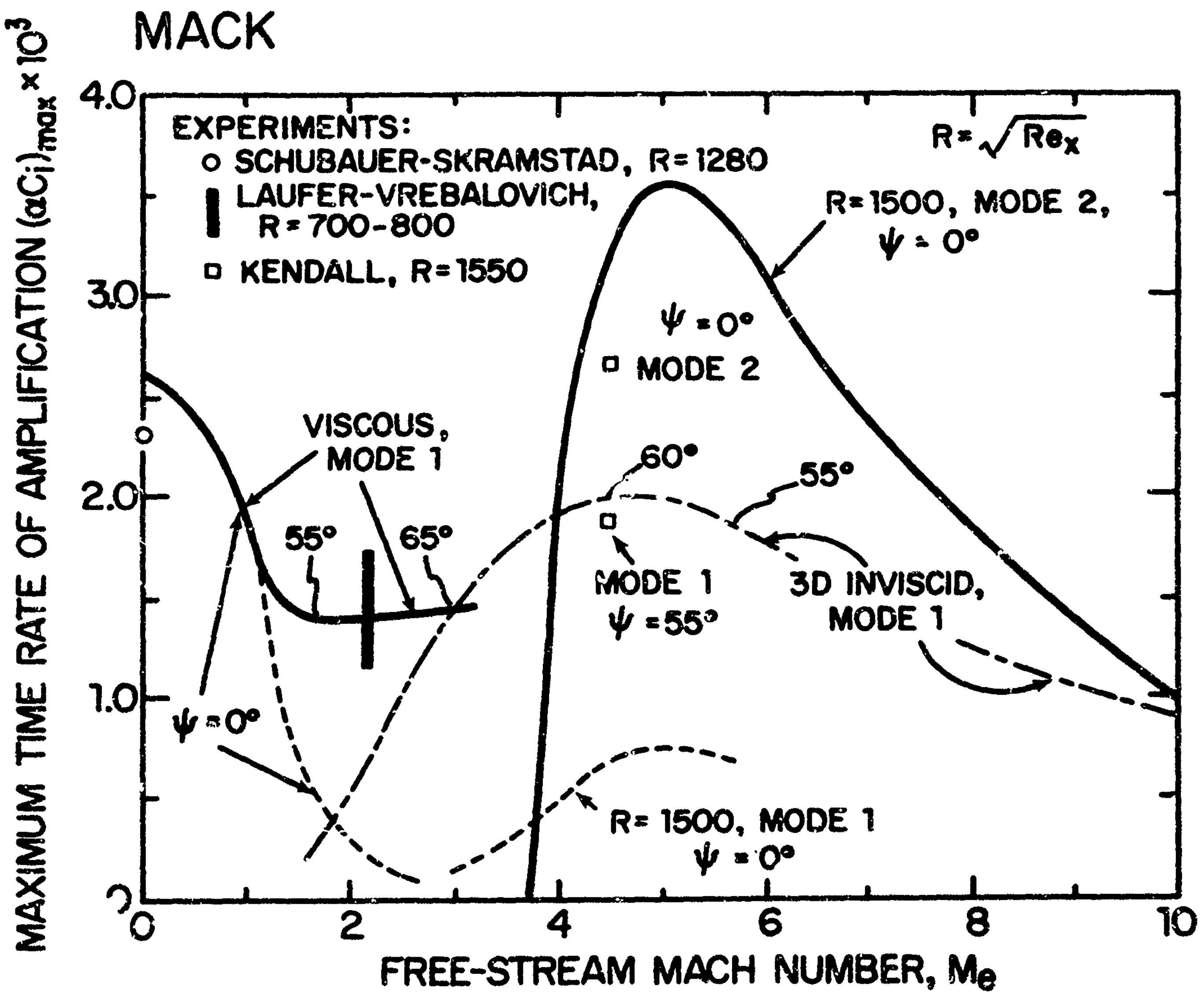
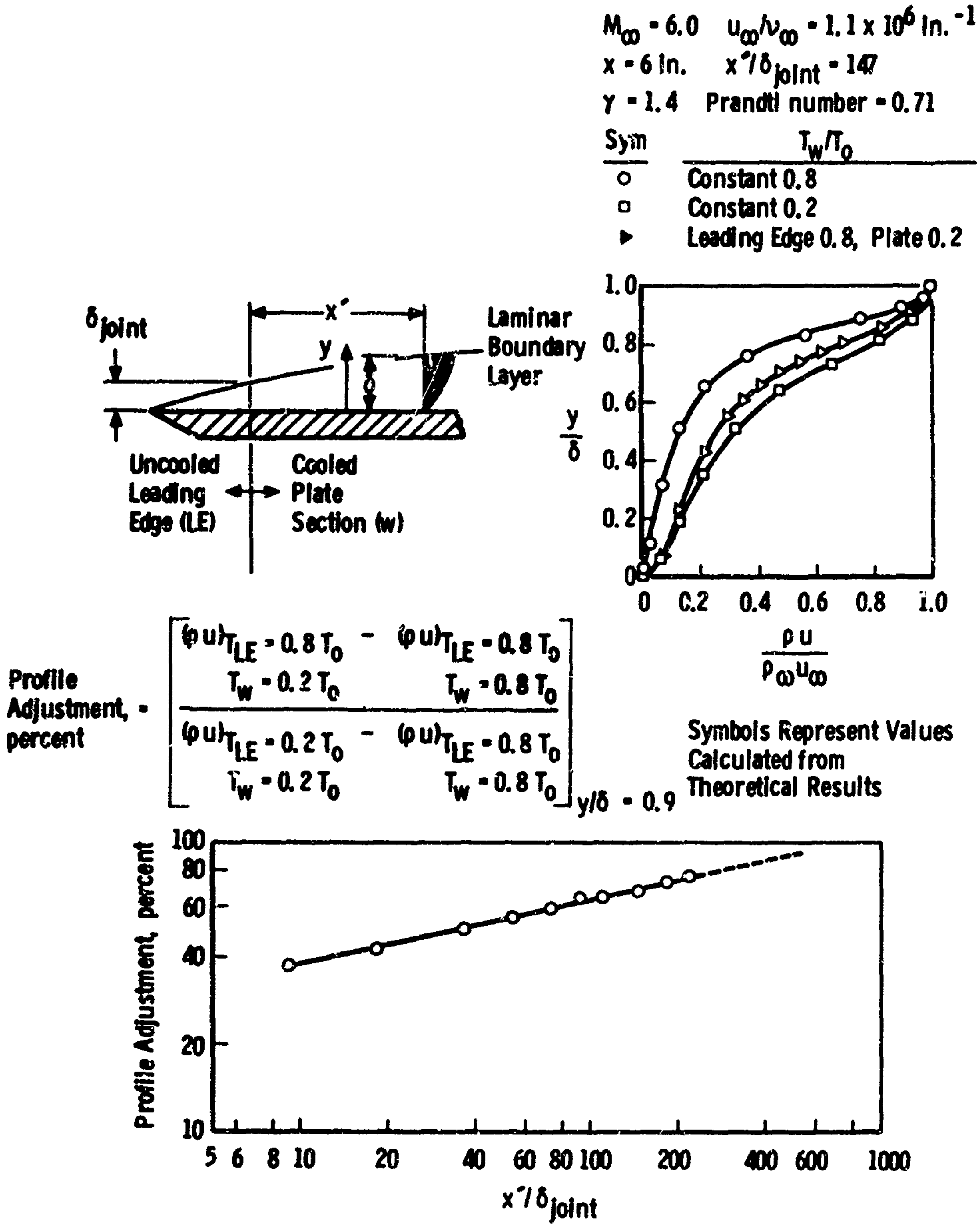


Fig. 10 - Summary Of Maximum Temporal Amplification Rates Of First And Second Modes As Functions Of Mach Number



a. Density-Velocity Ratio Profiles

Fig. 11 - Theoretical Effect Of Uncooled Leading Edge On Cooled Plate Boundary-Layer Profiles

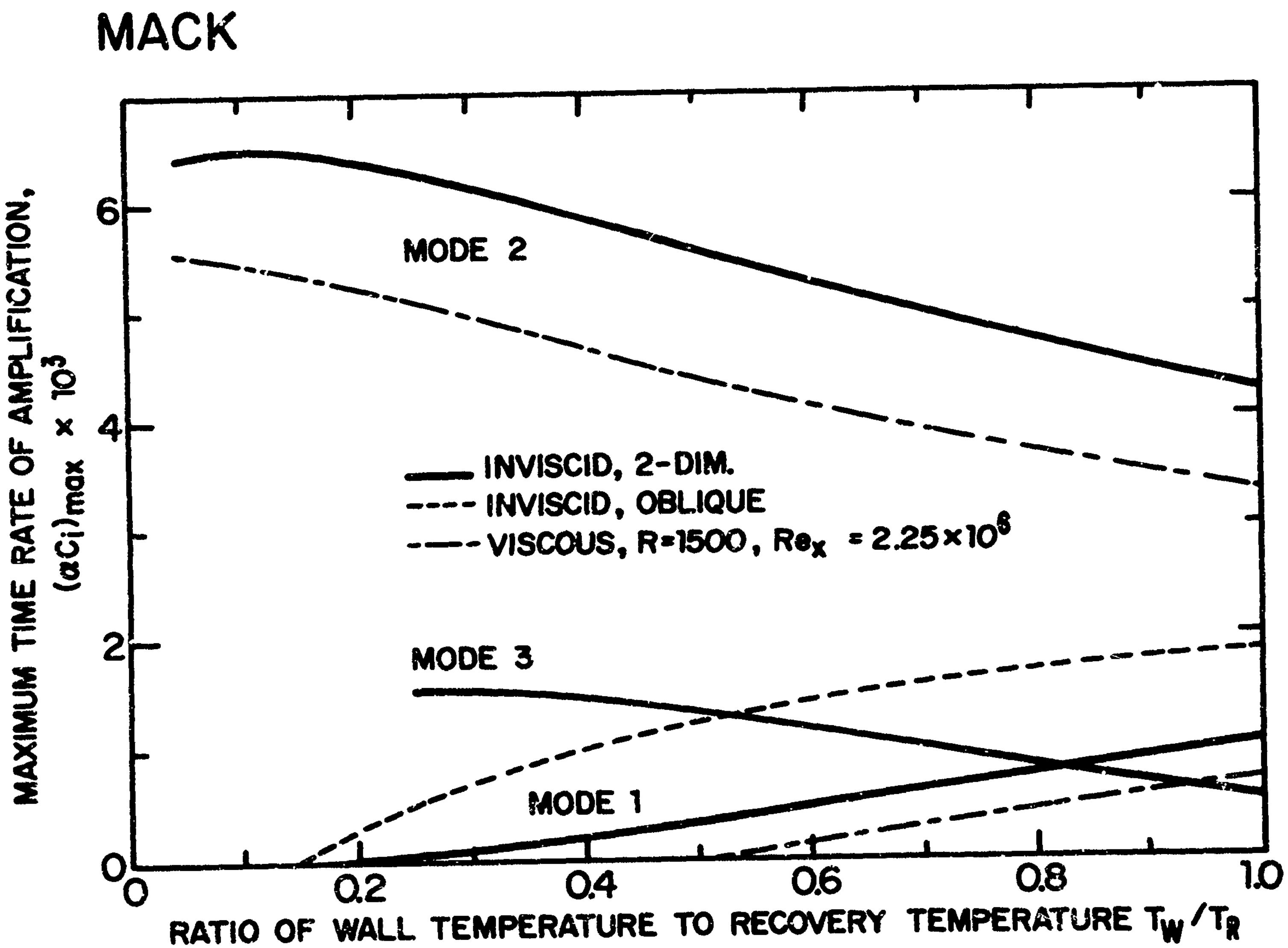


Fig. 12 - Effect Of Cooling On Maximum Amplification Rates $M_e = 5.8$

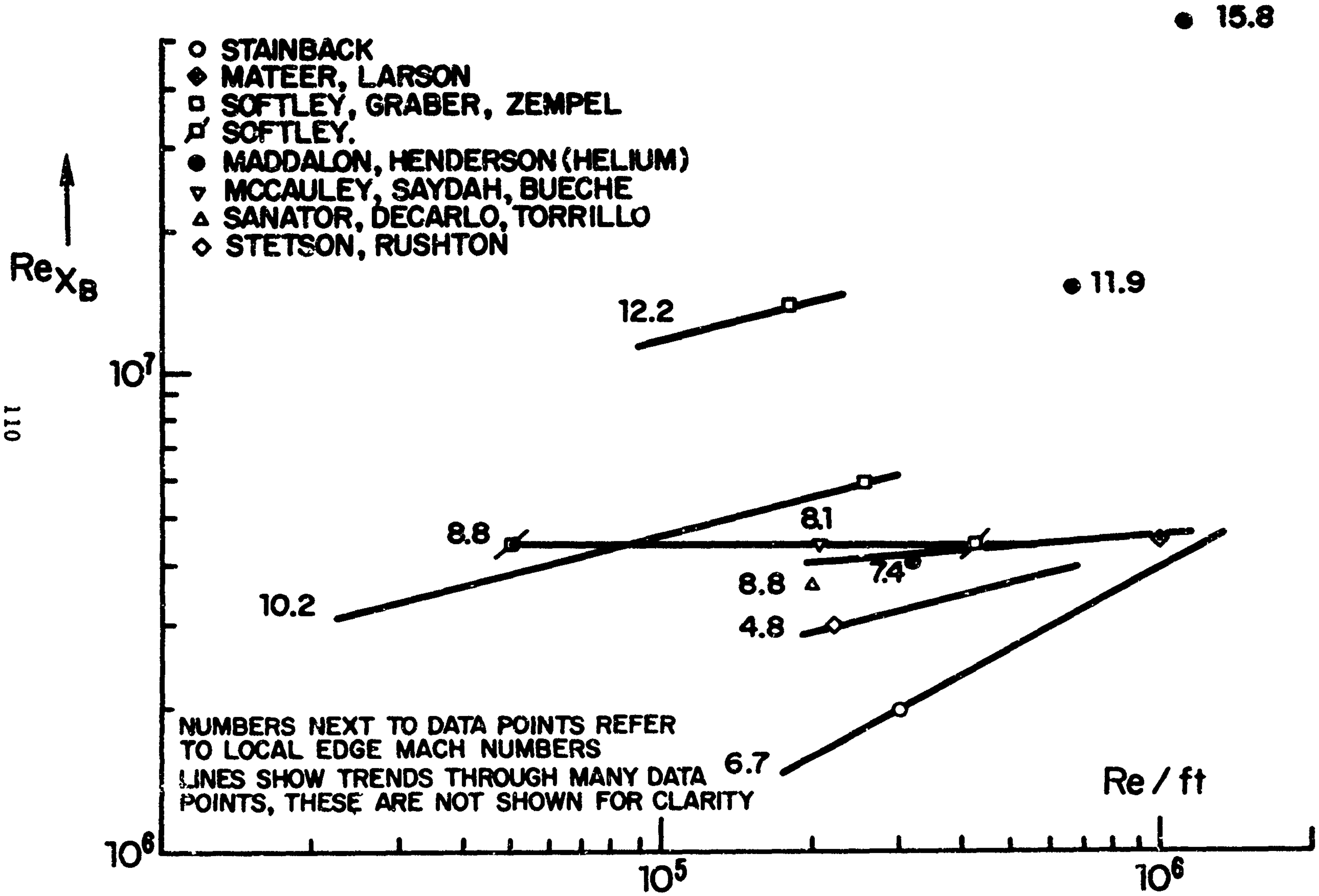


Fig. 13 - Comparison Of Transition Reynolds Numbers In Different Facilities
Sharp Slender Cone - Uniform Wall Temperature

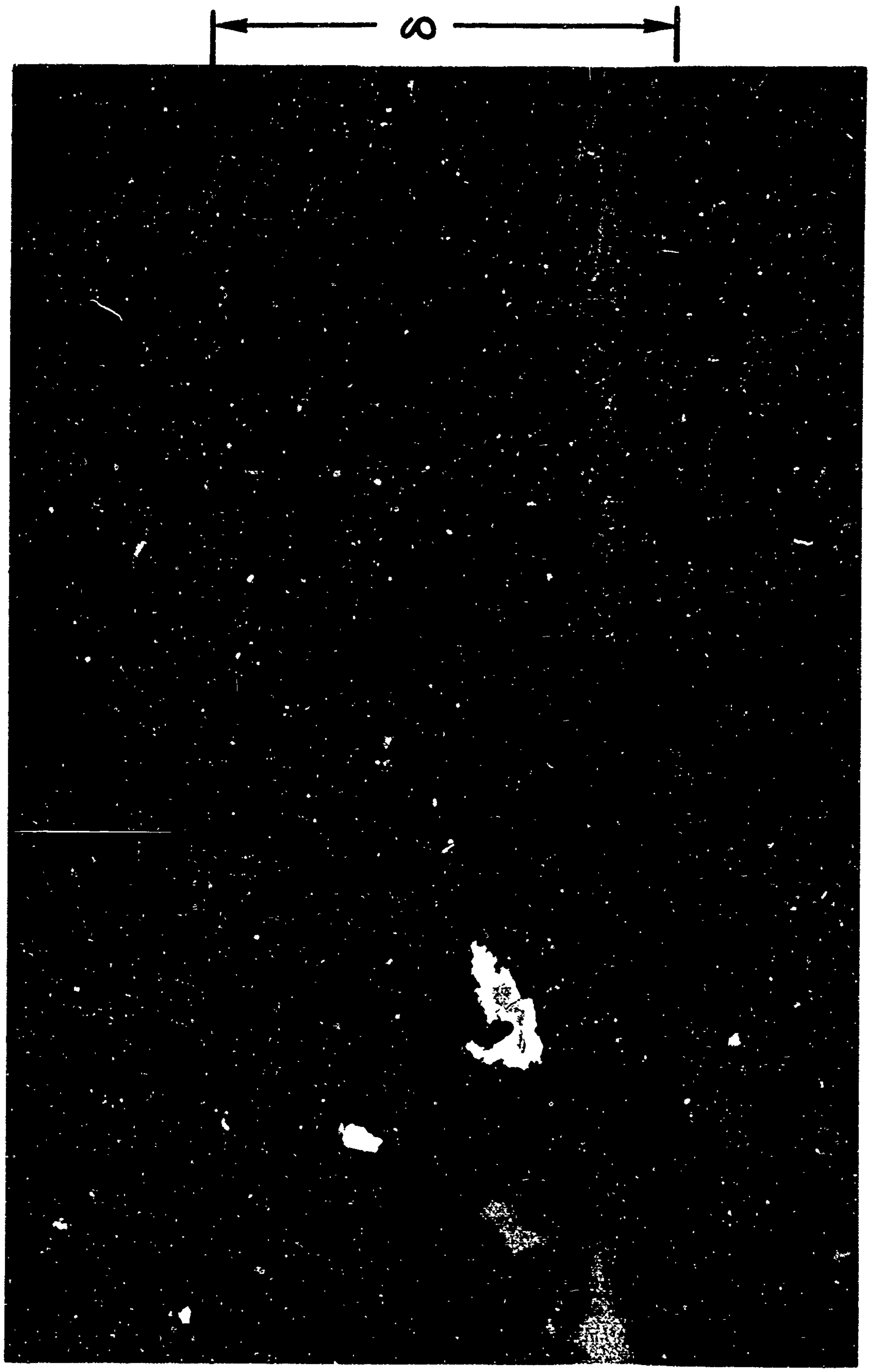
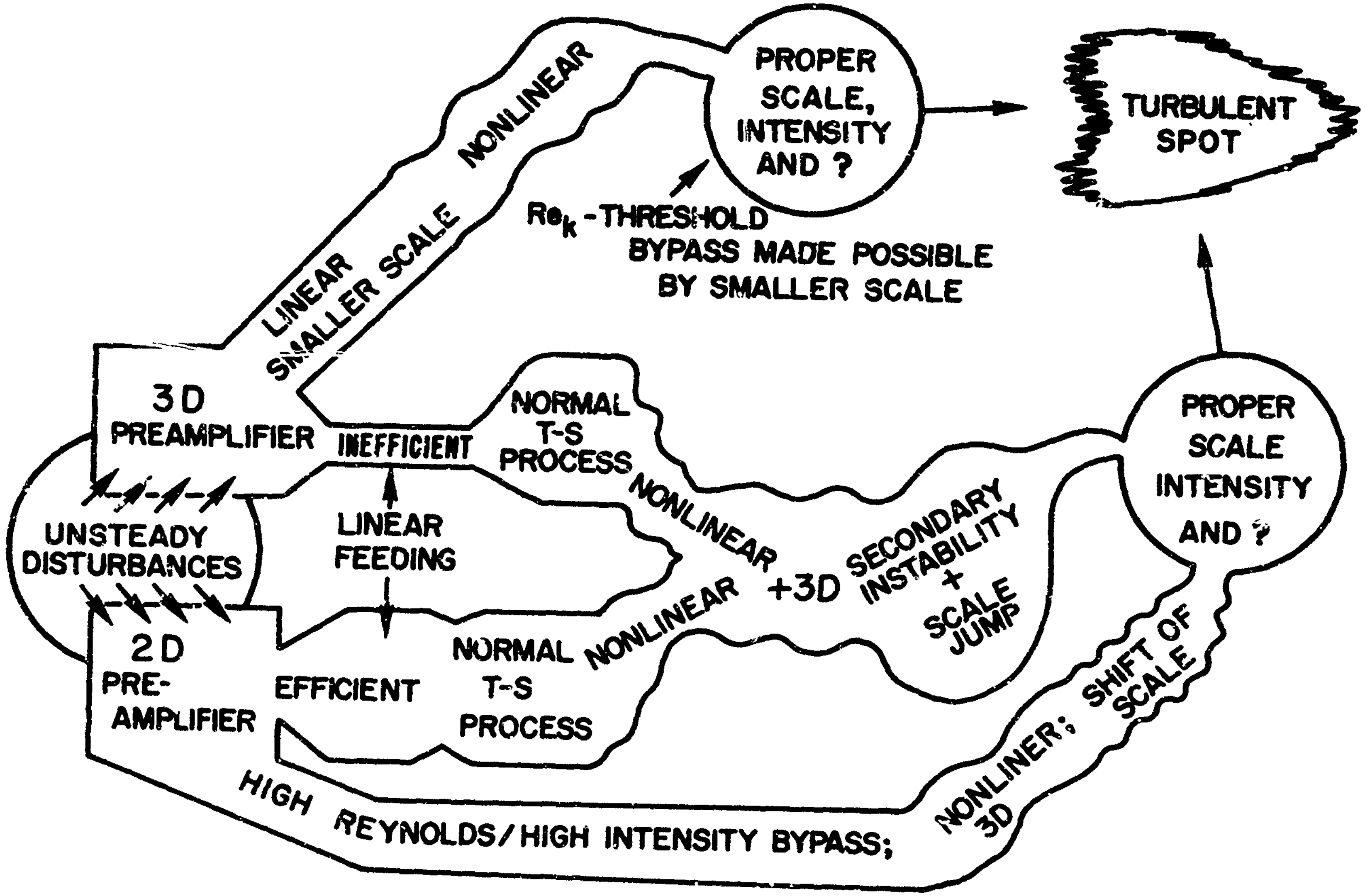


Fig. 14 - Subcritical Nonlinear Vortex Shedding From Cylinder Inside Boundary Layer



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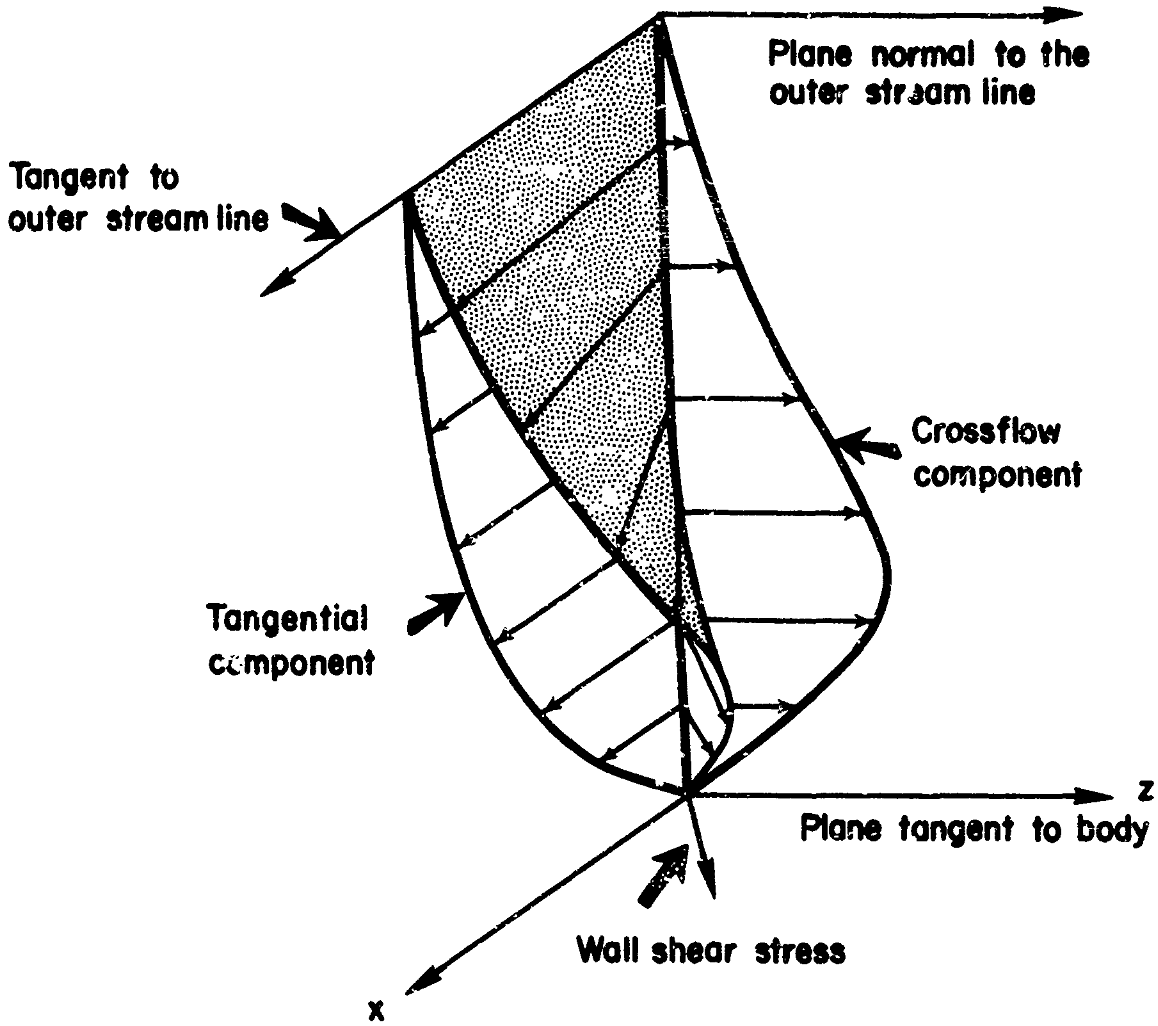
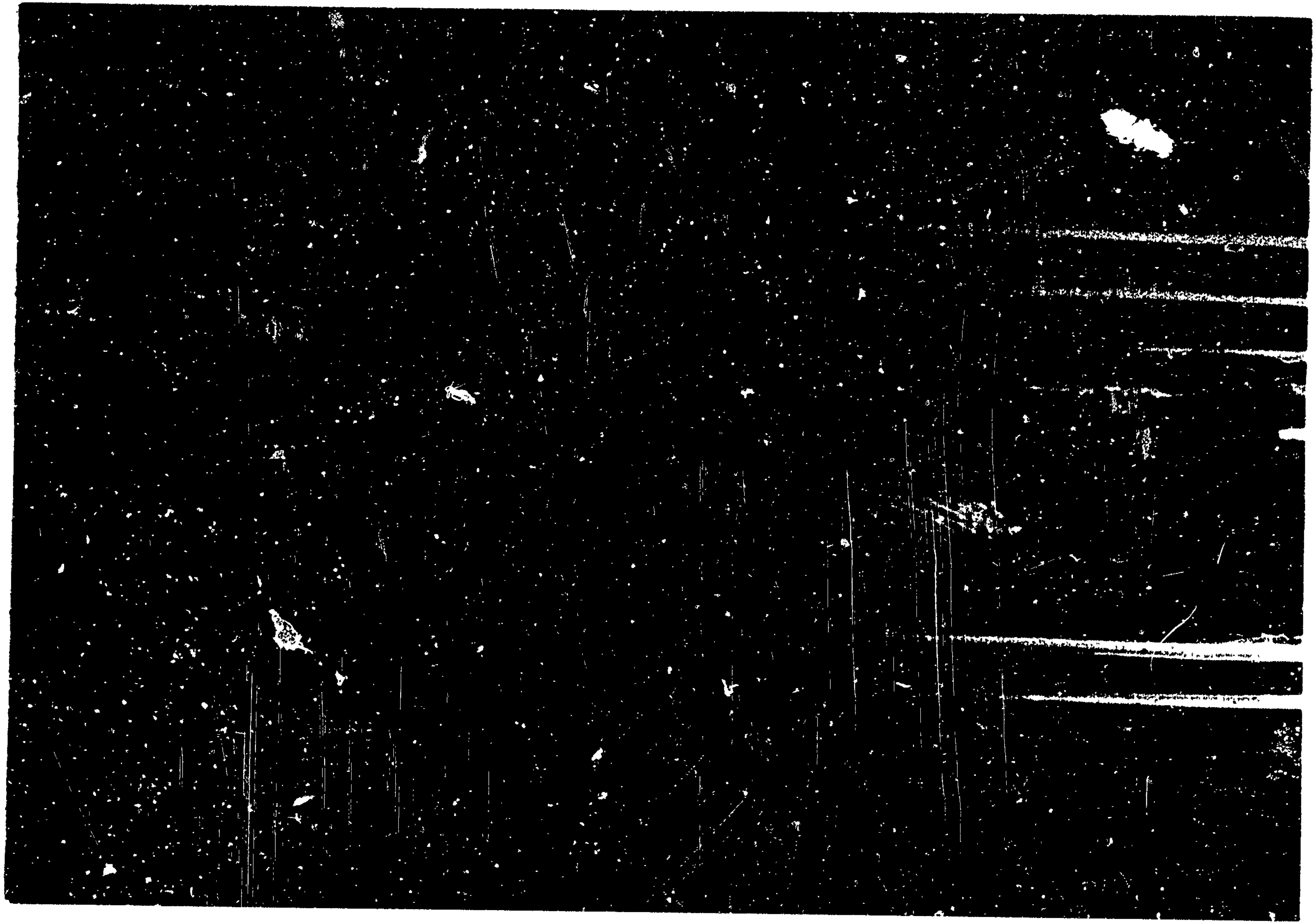


Fig. 16 - Velocity Profiles In A Three-Dimensional Boundary Layer



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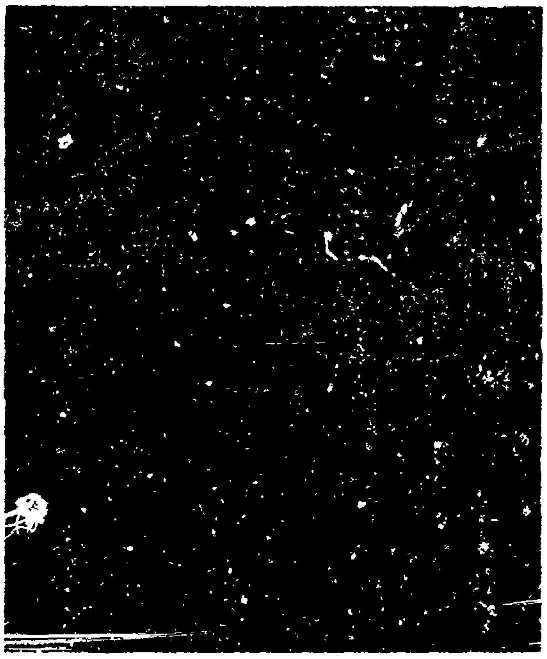
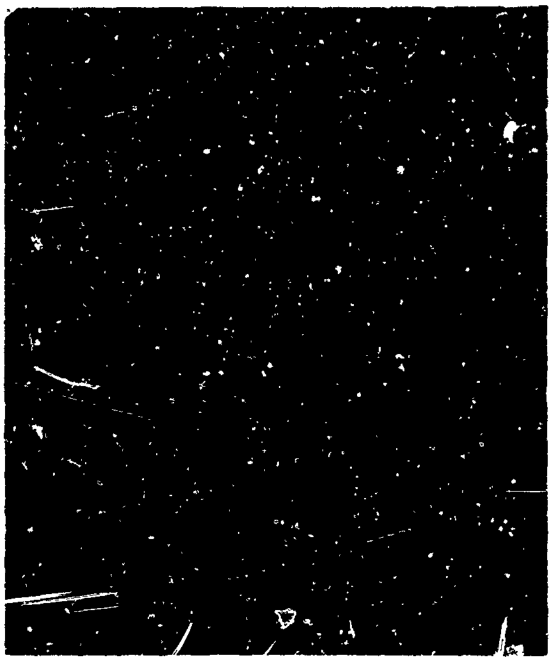
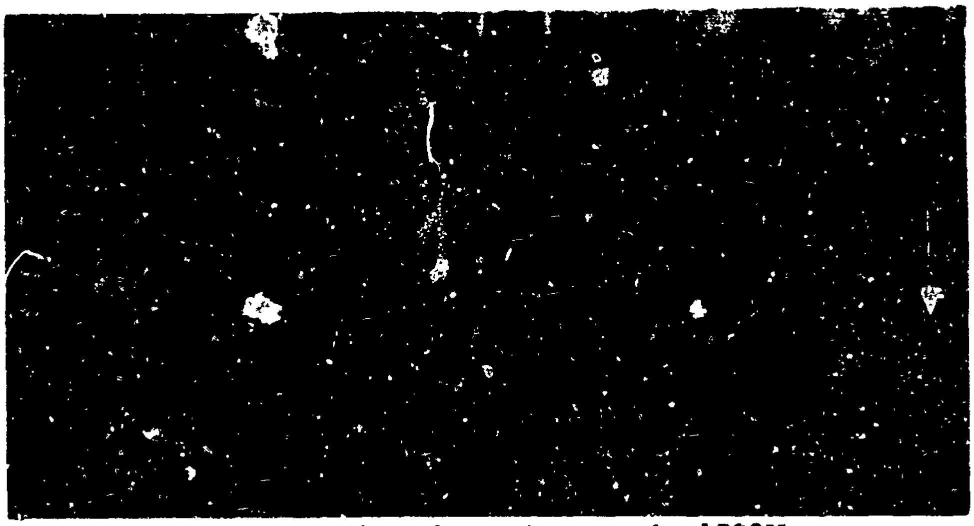


(a) Photomicrograph; 260X

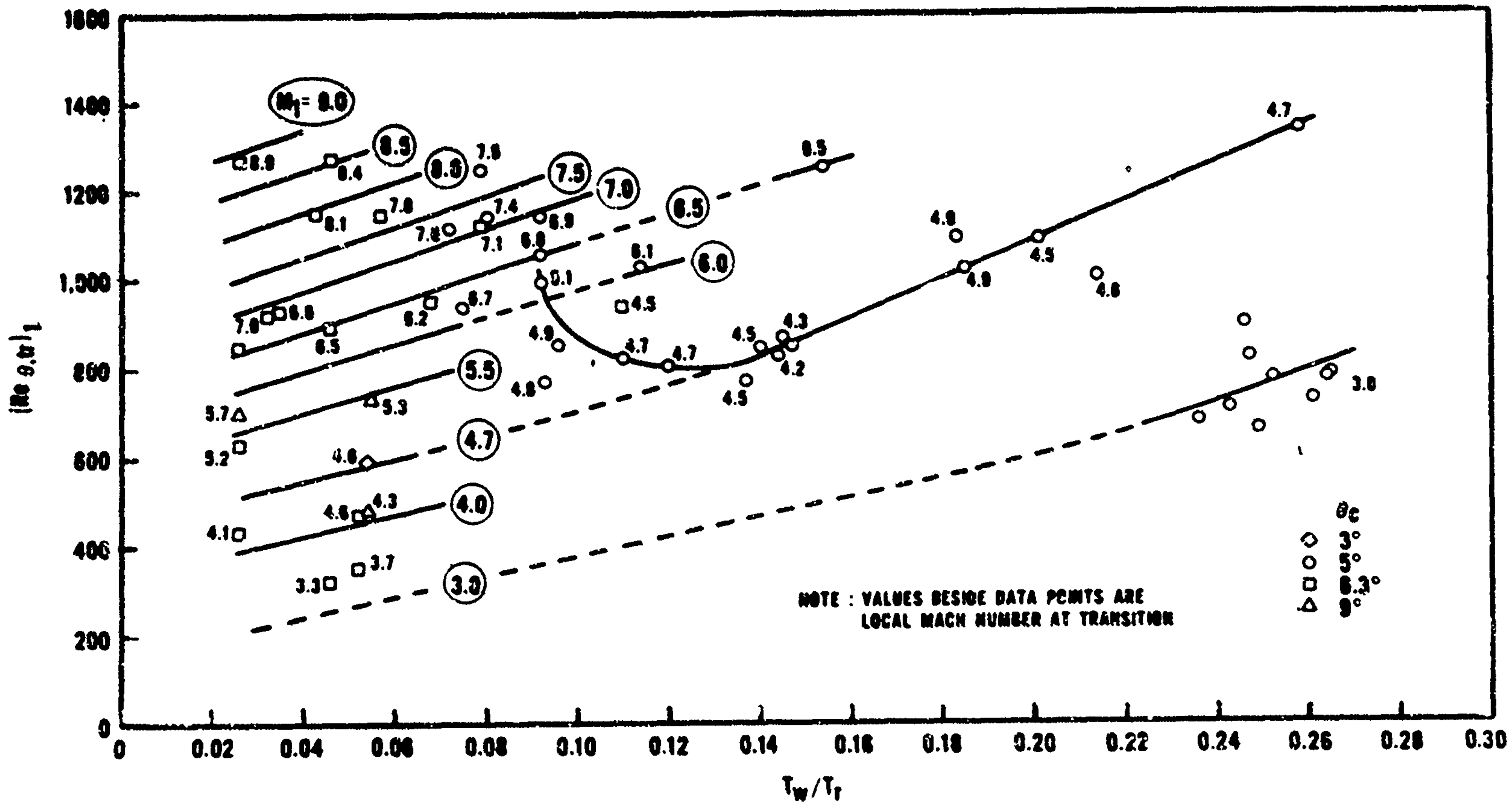


(b) Interferogram; 260X



(c) Wire shadow photomicrograph; 1700X.
(Arrow indicates direction of light)

Fig. 18 - Means of Viewing Small Roughness. Illustration Of Damage By Normal Profilometer Stylus



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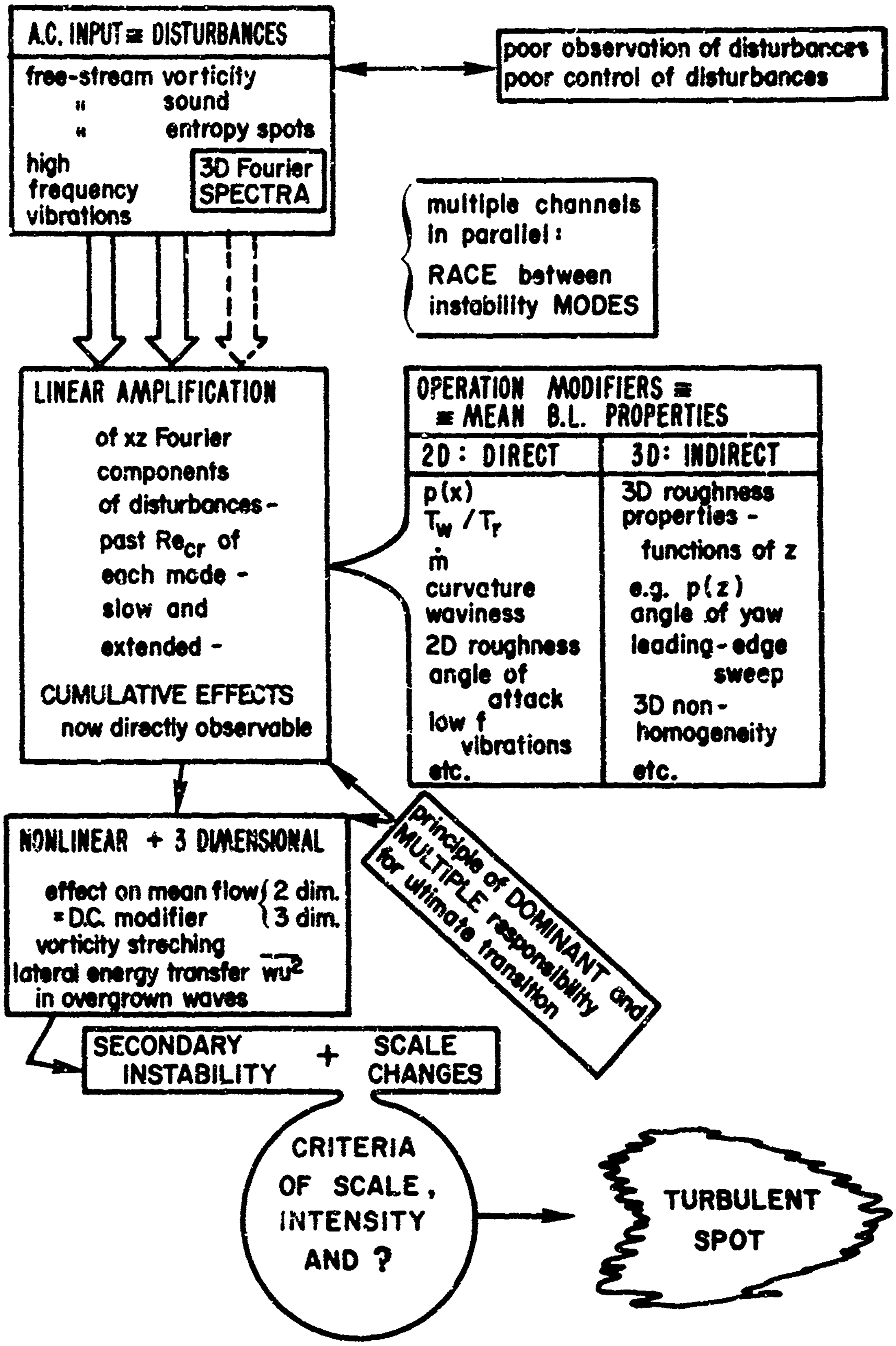


Fig. 20 - Laminar Boundary Layer As Á Linear And Nonlinear Operator

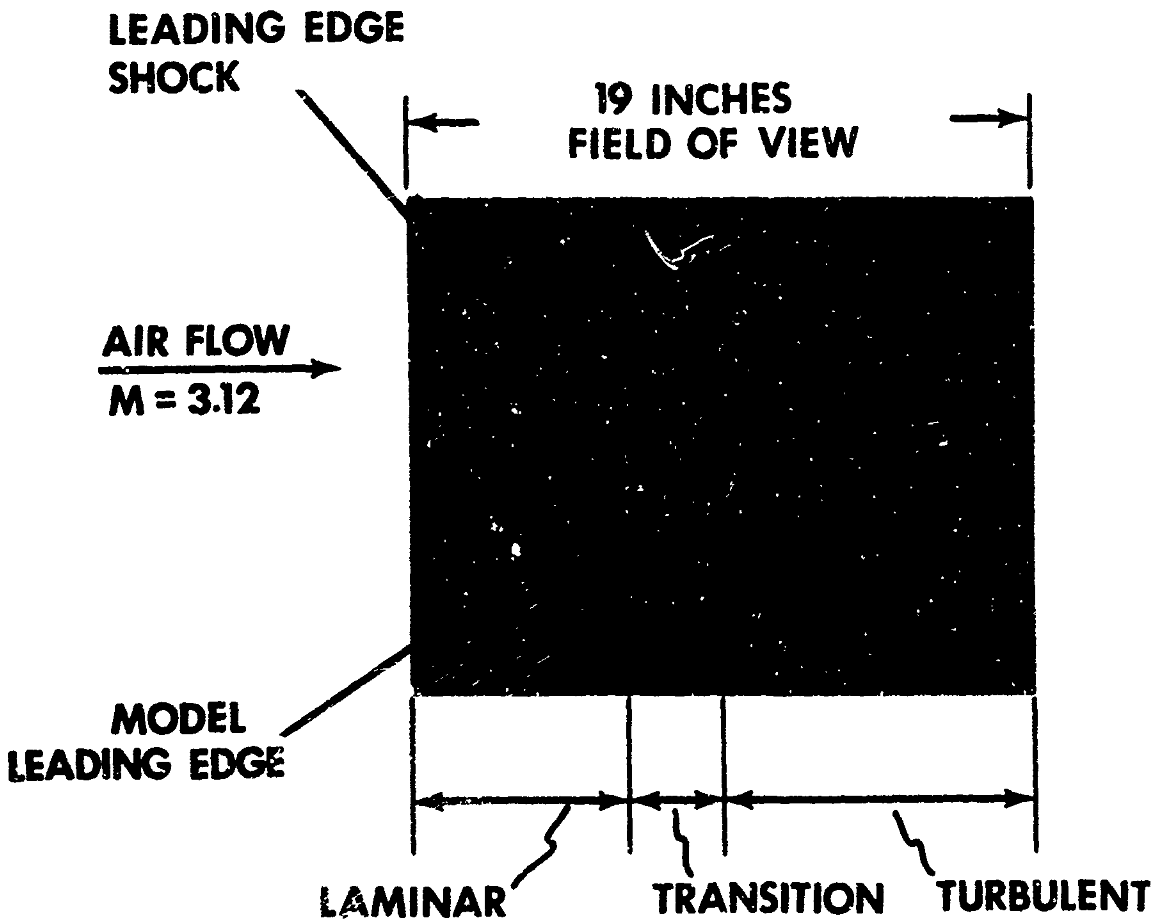


Fig. 21 - Cylindrical-Lens Enlargement Of A High-Speed Movie Frame Showing Sound Disturbances And Transition On A Hollow Cylinder

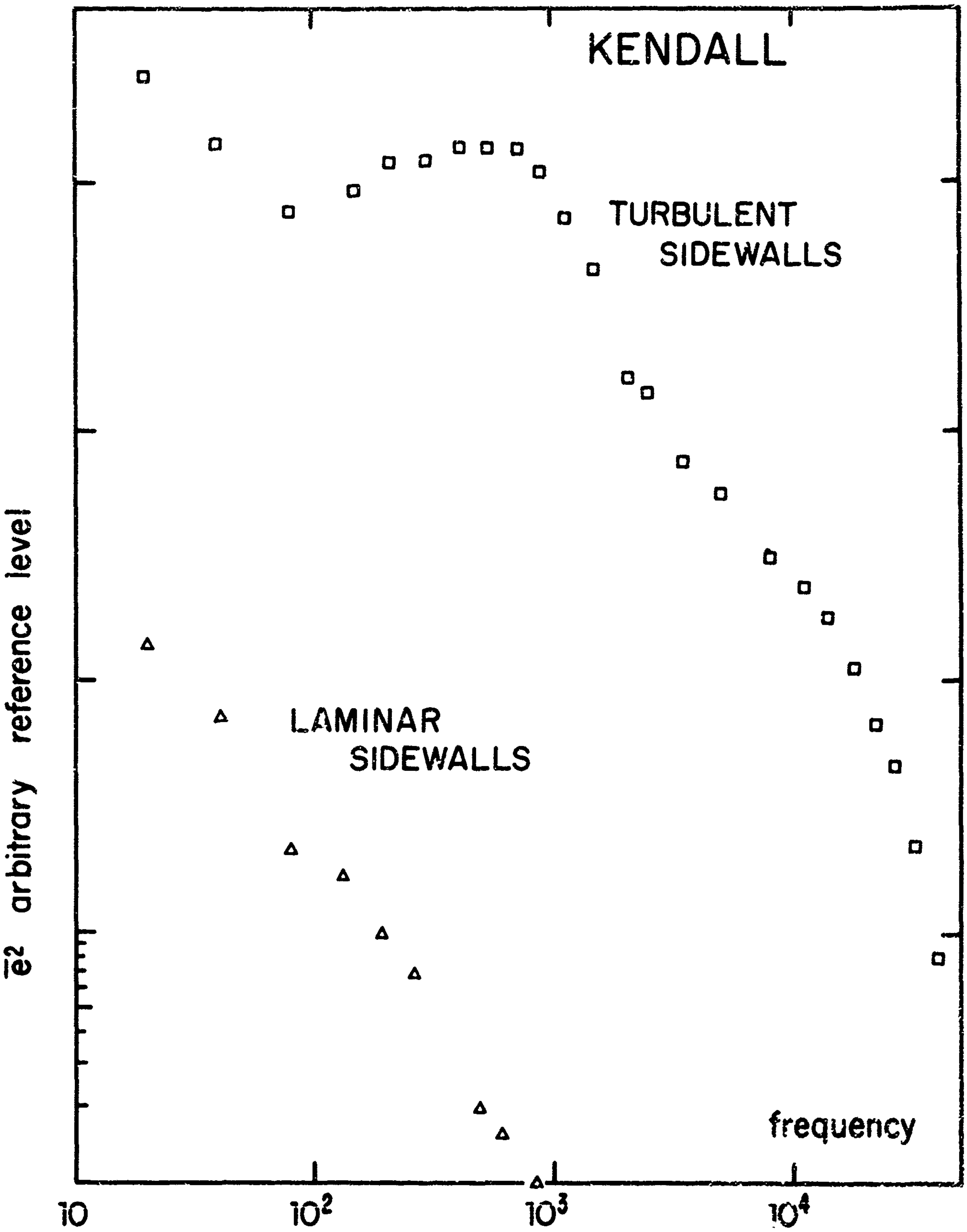
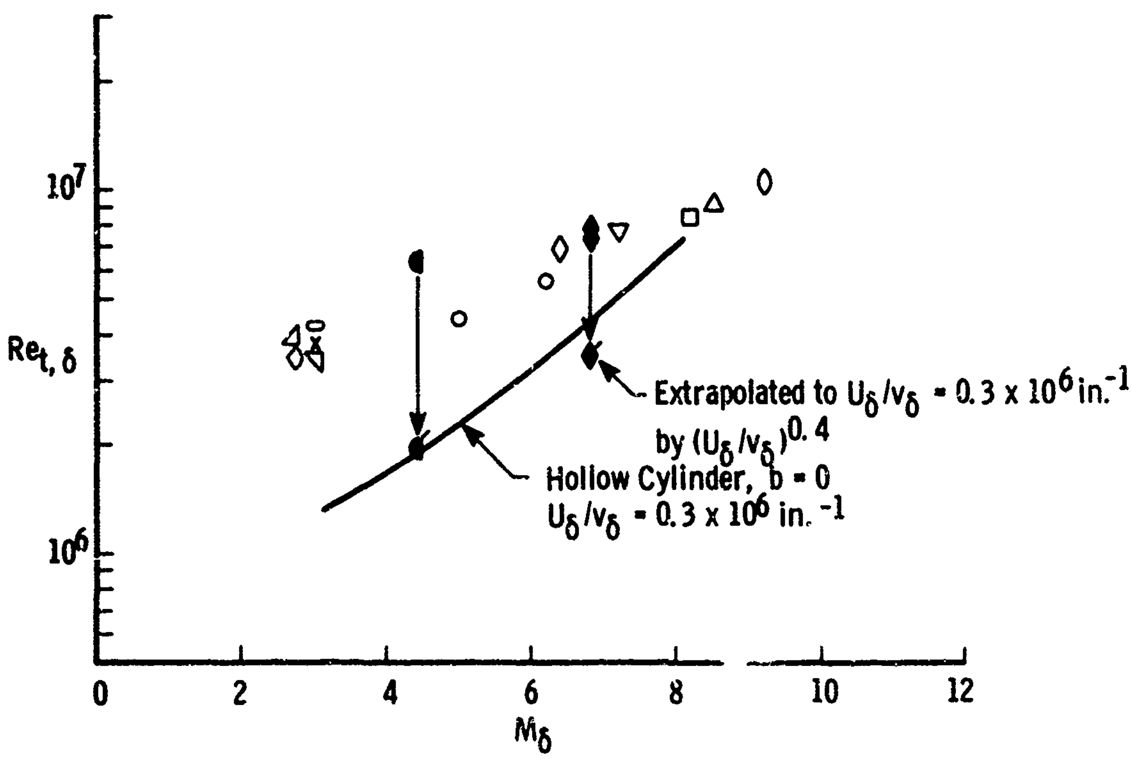


Fig. 22 - Spectra Of Free-Stream Fluctuation At M = 4.5 With And Without Turbulence Generated Sound

	Symbol	θ_c, deg	Tunnel	$U_\delta/v_\delta \times 10^{-6}$ in.$^{-1}$
Cones	◇	9	VKF (F)	0.3
	◖	10	VKF (Range K)	1.76
	◖	10	VKF (Range K)	0.3*
	○	10	VKF (E)	0.3
	△	6	VKF (C)	0.3
	□	7.1	VKF (C)	0.3
	◇	9	VKF (B)	0.3
	▽	10	VKF (C)	0.3
	▽	10	NASA (Lewis)	0.3
	△	10	JPL	0.3
	◇	10	JPL	0.3
	⬭	10	NASA (Lewis)	0.3
	◆	5	VKF (Range G)	1.76 - 2.26
	◆	5	VKF (Range G)	0.3*
Hollow Cylinders ($b \approx 0$)	—	-	VKF (D, E, B)	0.3
	x	-	PWT (16S)	0.3*

*Extrapolated



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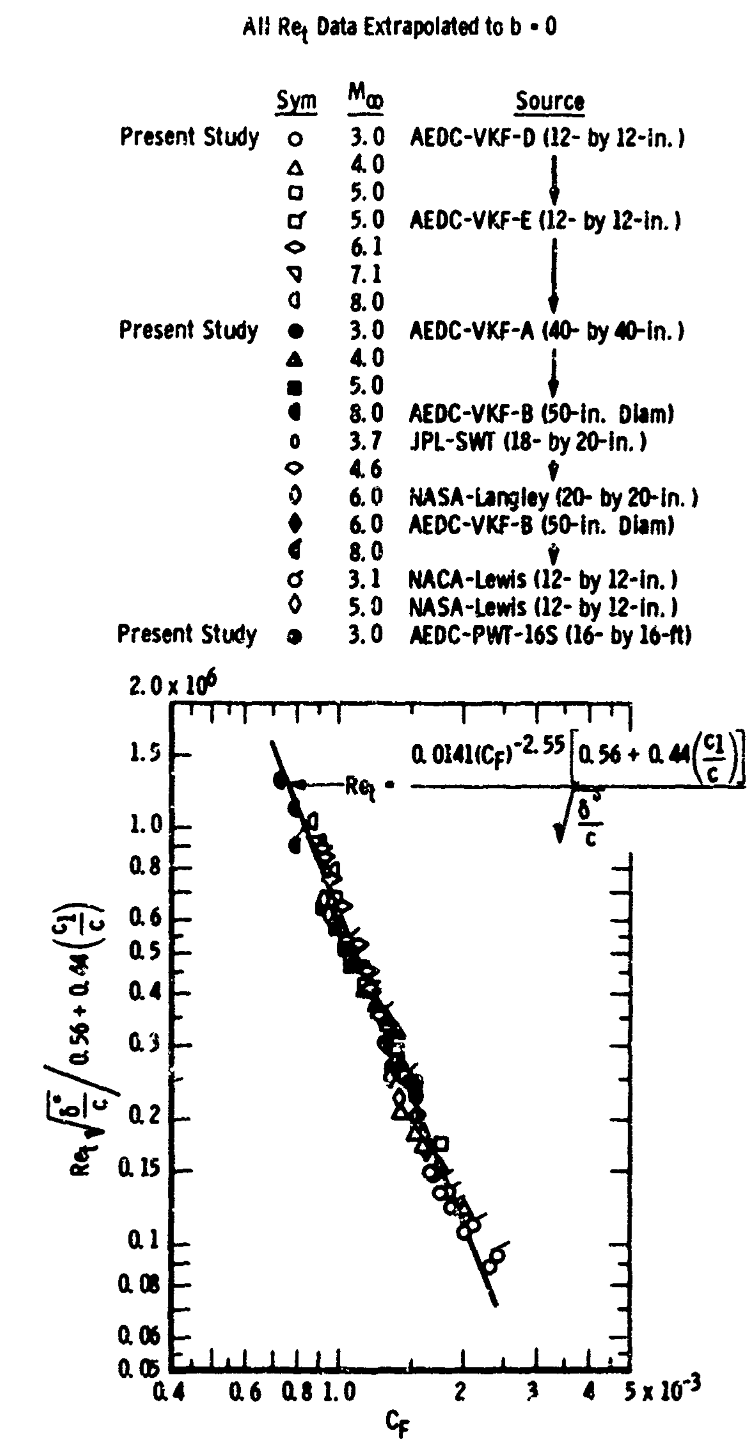
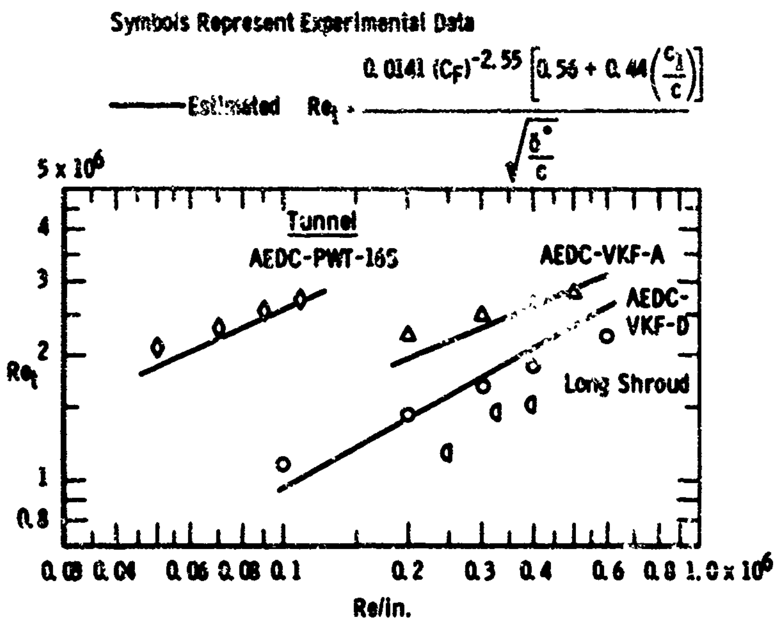


Fig. 24 - Correlation Of Transition Reynolds Numbers From Ten Wind Tunnels, Based On Aerodynamic Noise Parameters



Tunnel Size and Unit Reynolds Number Effect at $M_\infty = 3.0$, b = 0

Fig. 25 - Comparison Of Measured And Estimated Transition Reynolds Numbers From Several Tunnels

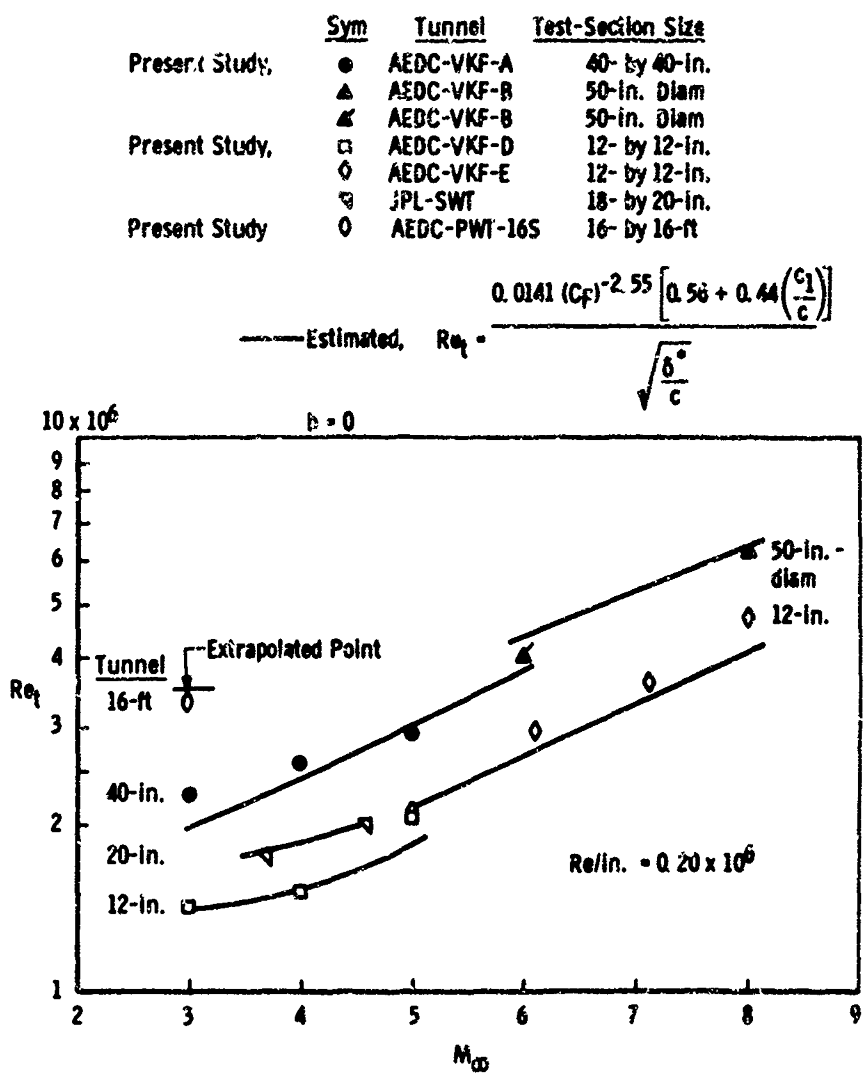
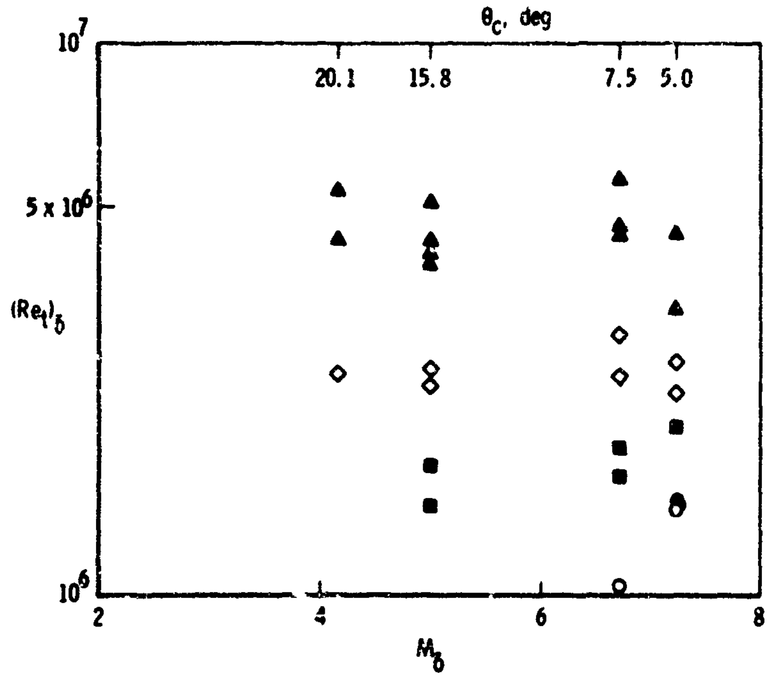


Fig. 26 - Variation Of Transition Reynolds Number With Increasing Tunnel Mach Number

		θ_c, deg	
		5, 20.1	7.5, 15.8
Sym	$(Re/in.)_\delta \times 10^{-6}$	$(Re/in.)_\infty \times 10^{-6}$	$(Re/in.)_\infty \times 10^{-6}$
○	0.116	0.092	0.082
■	0.224	0.18	0.16
◇	0.483	0.38	0.34
▲	1.17	0.93	0.83

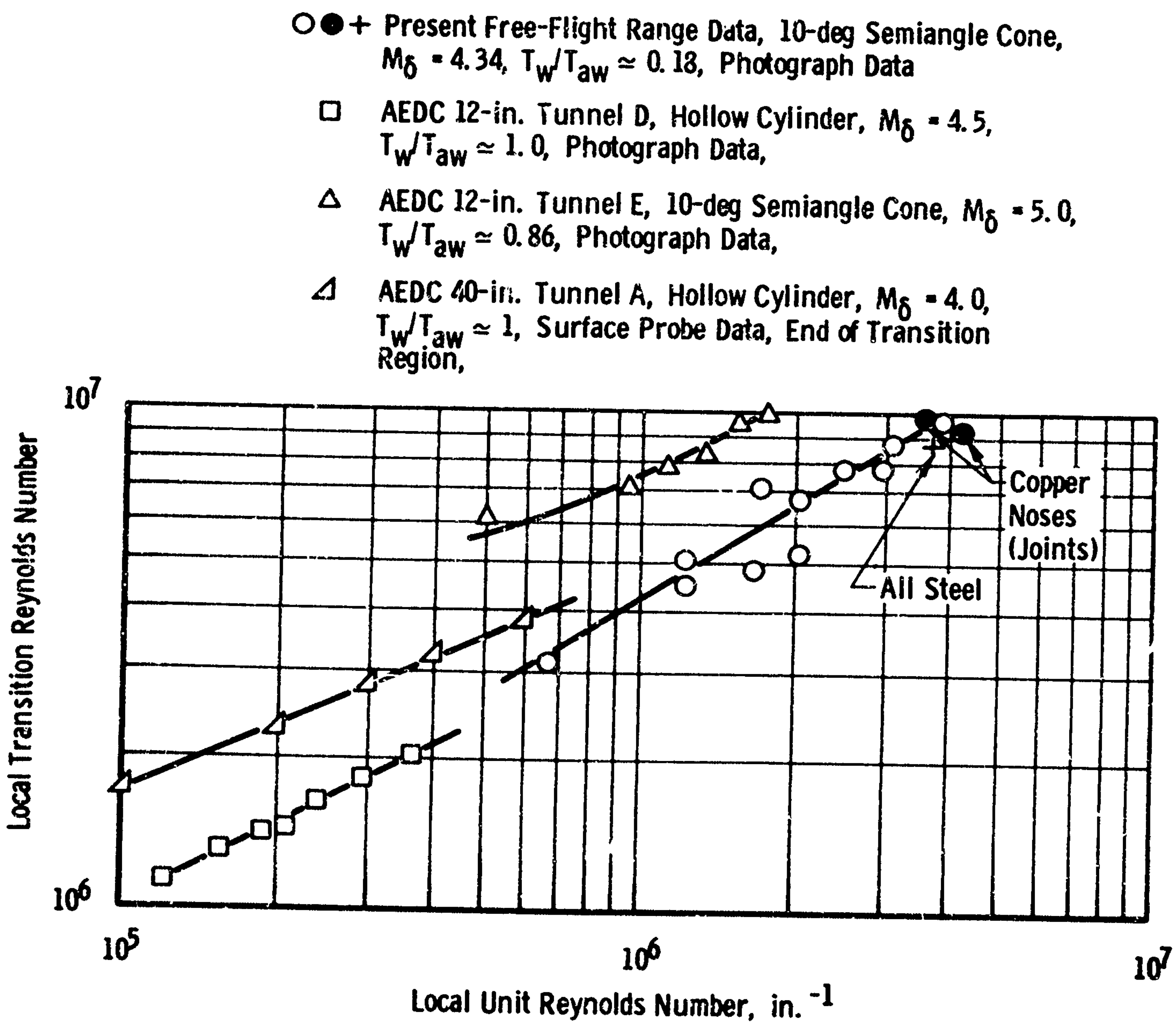
$(Re_t)_\delta = (Re/in.)_\delta \, x_t$

x_t determined from heat transfer data obtained using fusible paint.



Sharp Cones at $M_\infty = 8$

Fig. 27 - Stainback's Constant Local Unit Reynolds Number Experiments On Transition



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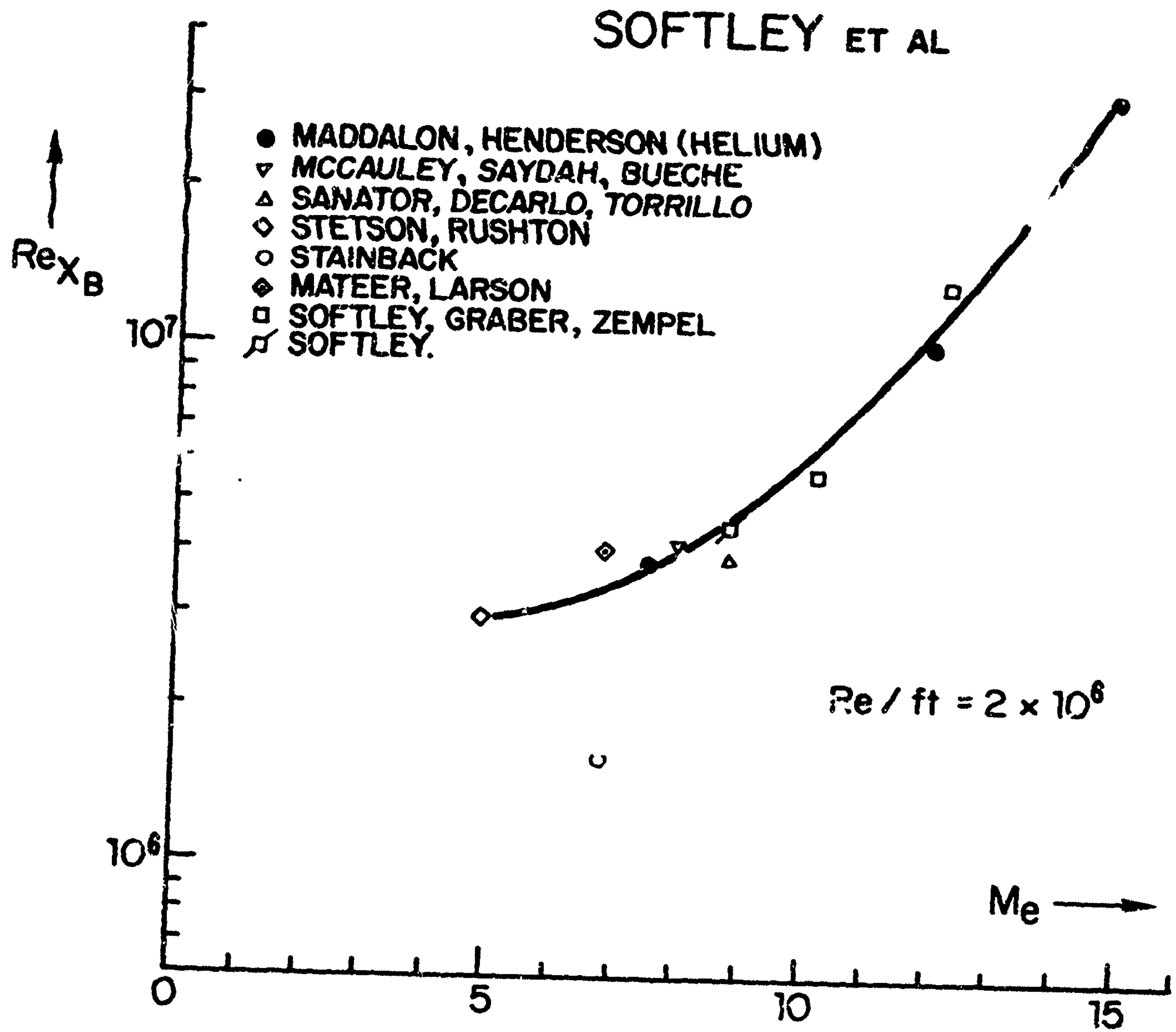
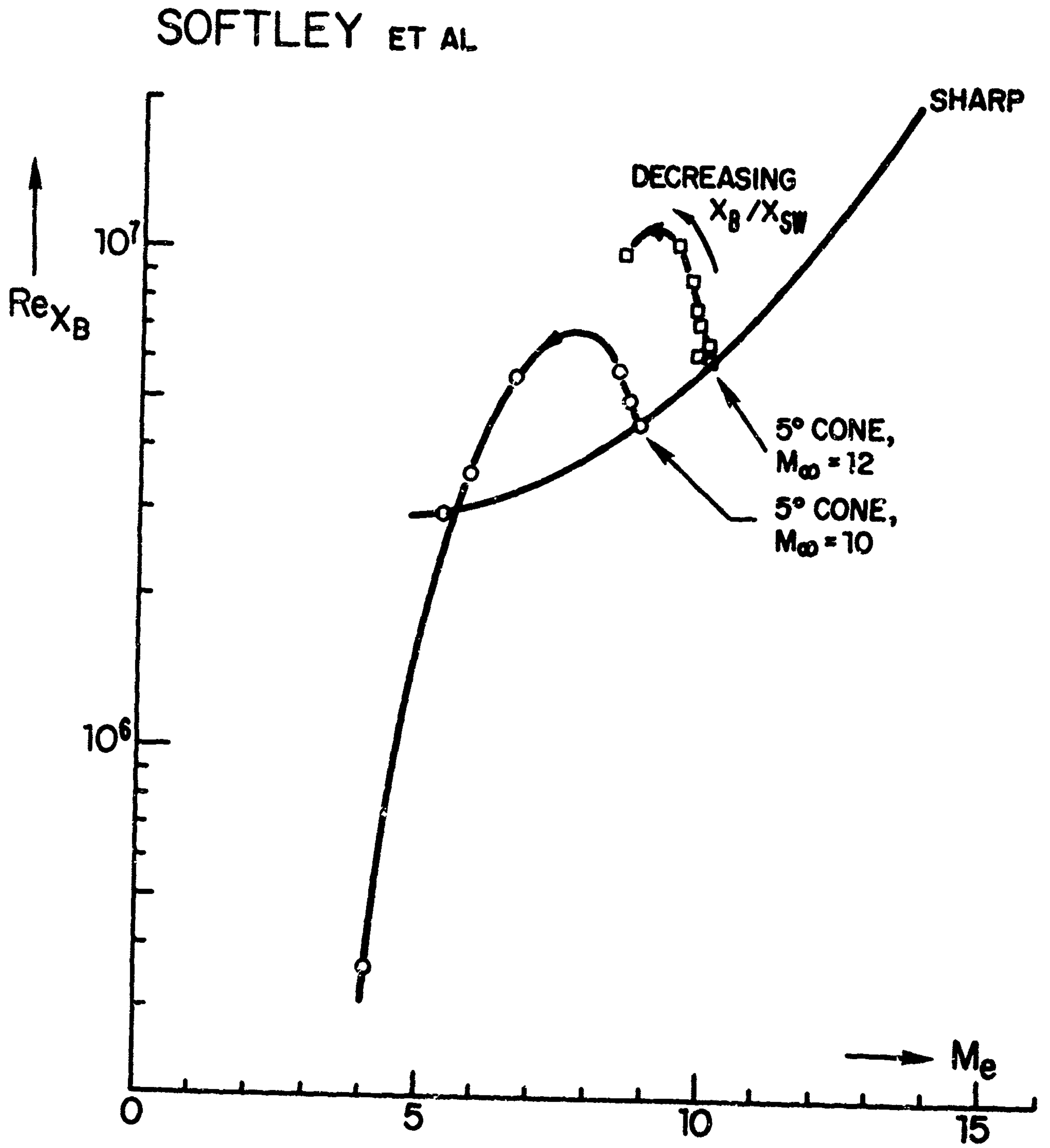


Fig. 29 - Effect Of Local Mach Number On Transition Reynolds Number-Sharp Slender Cone-Uniform Wall Temperature



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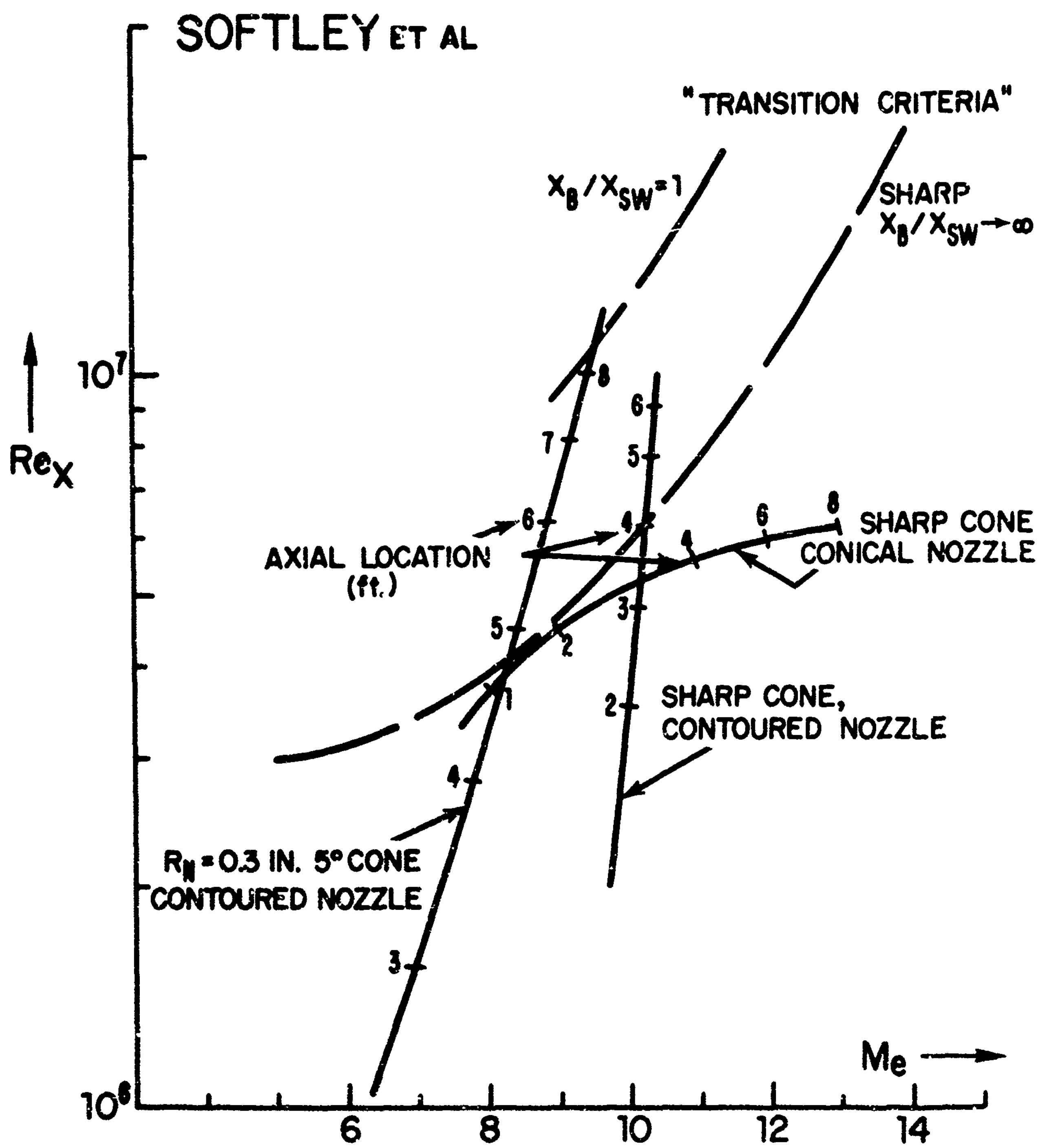

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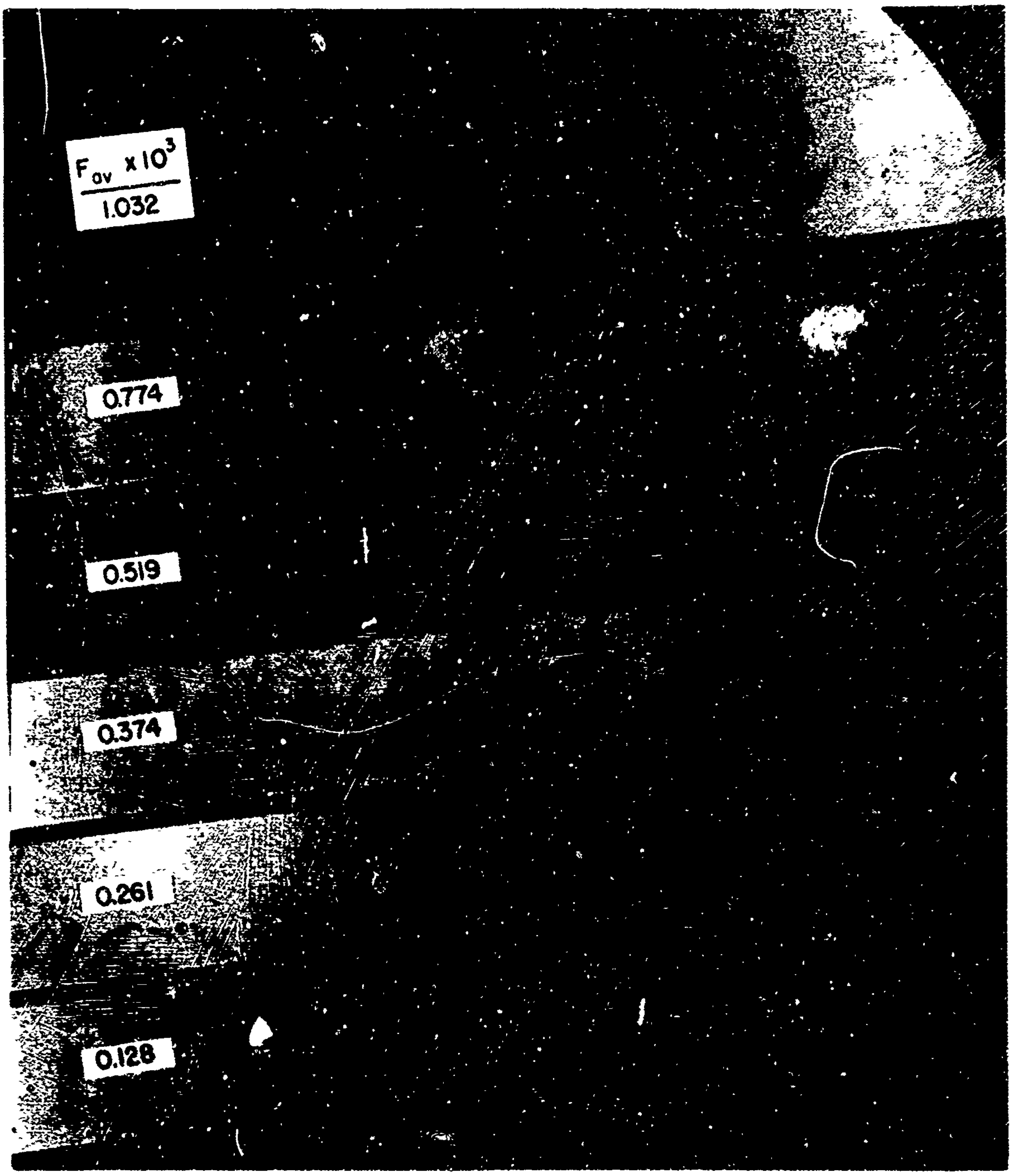

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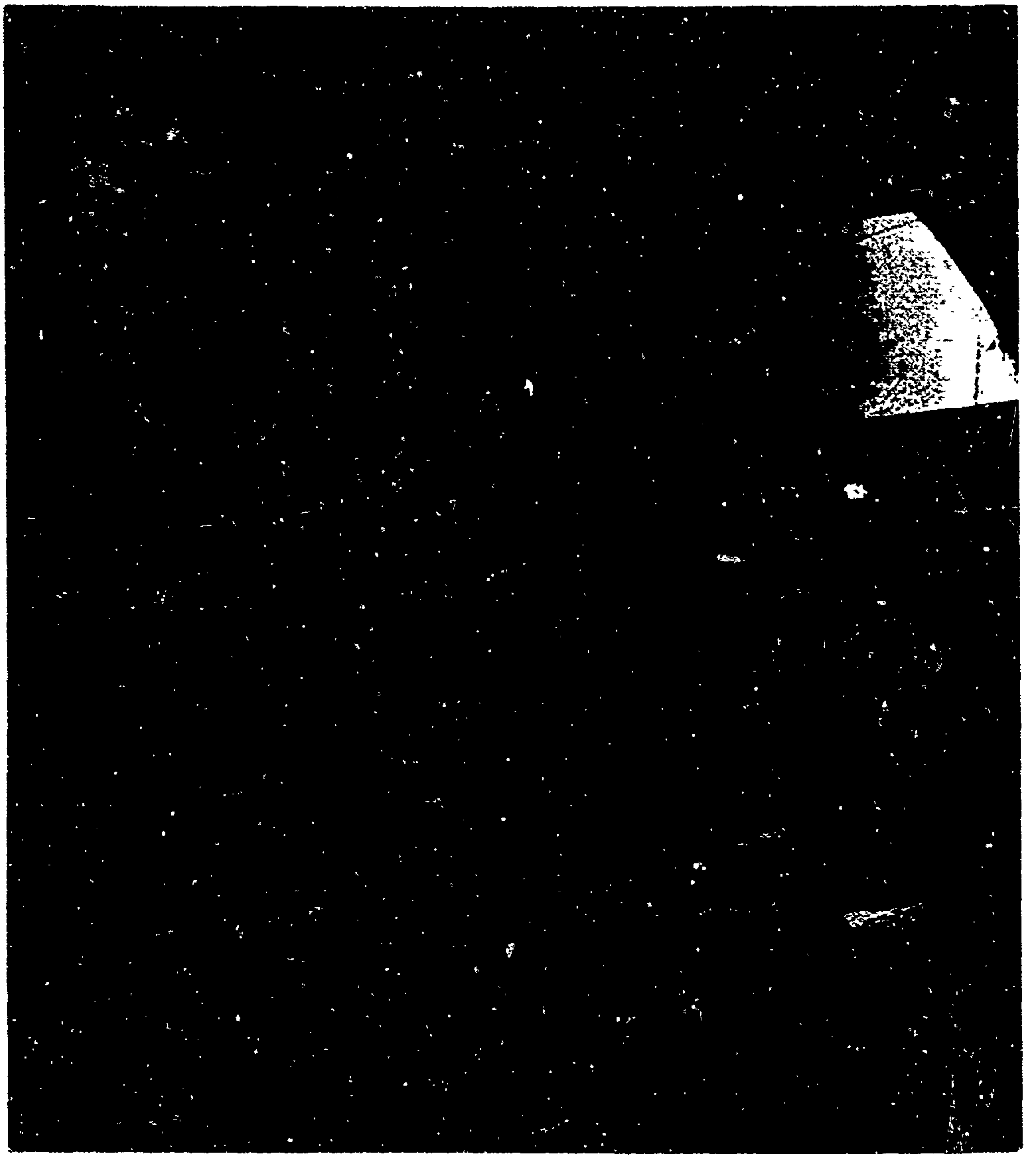

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UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Research Institute for Advanced Studies (RIAS) 1450 South Rolling Road Baltimore, Maryland 21227	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE
"CRITICAL EVALUATION OF TRANSITION FROM LAMINAR TO TURBULENT SHEAR LAYERS WITH EMPHASIS ON HYPERSONICALLY TRAVELING BODIES"

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report (April 10, 1967 to August 30, 1968)

5. AUTHOR(S) (First name, middle initial, last name)
Mark V. Morkovin

6. REPORT DATE December 1968	7a. TOTAL NO. OF PAGES 140	7b. NO. OF REFS 345

8a. CONTRACT OR GRANT NO. F33615-67-C-1662 b. PROJECT NO B.P.S. No. (680100-61430014) c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) TR-13c 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFFDL-TR-68-149

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Flight Dynamics Laboratory U. S. Air Force, AFSC Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

>This review report represents an attempt to evaluate critically the available data on high-speed boundary layer transition to turbulence and to interpret the apparent agreements and contradictions within some rational framework. Special attention was paid to the more documentable discrepancies between reported results as touchstones of conceptual models and instability theories. Experiments with "microscopic" information are used as backbone of conceptual models, both linear and nonlinear. Linear instability results are used as a point of departure for the examination of current controversial questions of transition reversal with cooling, unit Reynolds number effect, effect of aerodynamic noise in supersonic wind tunnels, etc. Hopefully, more discussion and clarification will be generated by the present at times blunt comments. Throughout, efforts at such clarification led to suggestions for possible fruitful research, theoretical, experimental, and applied. Many of the ideas put forward really represent a consensus of the many specialists at different laboratories the author had consulted. One of the objectives was to help to create such a consensus as to the best avenues of approach to hypersonic transition.

DD FORM 1 NOV 65 1473

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Security Classification

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Transition, Laminar-Turbulent						
Hypersonic Transition						

UNCLASSIFIED
Security Classification